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ORIGIN OF BANDED IRON DEPOSITS—A SUGGESTION.[1]

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ABSTRACT.

This essay is not self contained. In brief extracts it is impossible adequately to summarise such papers in ECONOMIC GEOLOGY as those of Moore and Maynard, Gruner, or Gill. It is assumed that the present contribution will be read in conjunction with those papers.

The suggestion here advanced is that the banded iron deposits of the older pre-Cambrian throughout the entire world represent epicontinental sediments formed as chemical precipitates from cold natural solutions in isolated closed basins on a land surface that had been reduced to the last limit of peneplanation.

Analogies are drawn with the "duricrust" of Australia, formed on a surface of somewhat less ideally perfect peneplanation during an era of low rainfall with marked seasonal incidence. The exceedingly small probability of repetition of periods of such exceptionally perfect base-leveling is considered to explain the uniqueness in character of deposits of this type.

The writer is of opinion that, in most geological literature, exaggerated insistence on *marine* sedimentation is evidenced. Reasons are given for this view.

The necessity for critical consideration of admissibility of results of laboratory experiments in explaining geological processes is discussed.

INTRODUCTION.

IT may appear the height of presumption for one in the Antipodes to advance a suggestion regarding the origin of the banded iron deposits of the Lake Superior region, after the subject has been so carefully and exhaustively treated by such geologists as Van Hise,

[1] Published by permission of the Minister for the Interior, Commonwealth of Australia.

Leith, Gruner, Collins, Quirke, Thomson, Gill, Moore, Maynard and others. The statement by Moore and Maynard (3, p. 517),[2] that "a perusal of the literature gives no adequate explanation of the characteristic banding of iron and silica in the pre-Cambrian iron formations" indicates that any suggestion not contrary to demonstrable laws of nature is worthy of at least passing consideration, and provides an excuse for the present essay.

In Australia there exist certain geological conditions that do not appear to have been so pronounced in the countries surrounding the North Atlantic; and these conditions may have a bearing on the particular geological processes involved in the genesis of banded iron formations.

It is necessary briefly to review the ultimate basis of geological theory in regard to matters of the type under consideration.

DEVELOPMENT OF THEORIES.

The firm foundations of geology as a science rest upon what is usually referred to as the Doctrine of Uniformity, so strongly insisted upon by the father of British Geology, Sir Charles Lyell. Its principal thesis is that earth processes throughout geological time have always been essentially the same in type and extent. In other words, the study of existing earth processes provides the key to unlock the secrets of the past. Unquestionably this great doctrine cannot be assailed seriously, and must continue the sheet anchor of geological belief. It must, however, work both ways. If a given set of facts will not fit into the framework of the accepted version of the doctrine, it is the framework that must be extended and modified, always in accordance with the fundamental laws of nature.

Almost the whole of geological investigation leading to the formulation of geological laws and the development of geological theory has been carried out in Western Europe and North America, and the tacit assumption has gradually grown up that this area of the earth's surface is completely "normal" as regards the study of geological processes. Quite unconsciously there has

[2] Numbers in parenthesis refer to the bibliography at the end of the paper.

failed to develop as completely as is perhaps desirable the questioning attitude that, possibly, the whole gamut of potential geological activities may not be represented in typical form in this favoured and familiar environment.

One of the greatest geological generalizations of the last generation was the development of the theory of the peneplain by W. M. Davis of Harvard. Its application in every part of the world has thrown light on all phases of geological processes. Yet, in no part of the North Atlantic region does there appear to be preserved any great and continuous extent of geologically recent peneplanation. Orogenic and epeirogenic movements on a major scale during late Cenozoic time have rejuvenated the geographic cycle, and denudation by running water, with its sequel of transportation and deposition in the sea of dominantly clastic materials, is the "normal" feature in dynamic geology. North Atlantic geologists have been "born and brought up" on the obvious domination of "normal" dynamic activity, involving reduction of continental surfaces by running water and sedimentation almost entirely marine, except for minor deposits in lakes, which are essentially local expansions of "normal" river valleys.

Climatic factors, too, have come to be accepted more or less as a matter of course. Reasonably copious and well distributed rainfall produces rivers, which though they may vary seasonally in volume, are "normally" constantly running, and therefore constantly carrying on the functions that have come to be considered the normal ones for any self-respecting river.

True, there are minor and subordinate areas within which local and abnormal conditions prevail, such, for instance, as areas of internal drainage, swamps and marshes, and deserts; but, to the majority of investigators possessing a lifelong familiarity with "normal" conditions, such aberrant features very naturally appear to be local anomalies of insignificant importance.

This does not imply any lack of scientific perspective, or any narrowness of judgment; but infers only reasonable acceptance of the only environment with which the geologist is familiar, either by personal investigation or through the study of geological litera-

ture. Since, however, probably more than ninety-five per cent of both investigations and literature refer to the North Atlantic region, it is inevitable that there is a possibility of over emphasis on the restricted environment of that region. Only if there were evidence of a desire on the part of an investigator to torture facts and deductions to make them fit into the Procrustean bed of limited experience would such warping of scientific perspective become reprehensible.

PHYSIOGRAPHIC FEATURES AND CLIMATIC CONDITIONS IN AUSTRALIA.

In Australia there is an environment different in some respects from that of Western Europe and the United States of America. With land area and latitude closely comparable with the United States, Australia exhibits certain strong contrasts in geographical conditions, affecting markedly the processes of dynamic geology. Over most of the continental area the rainfall is strictly seasonal in incidence, and over much of it is quantitatively small. Over a region comparable in latitude and extent with the drainage basin of the Mississippi River system there is not a single permanently flowing river, and most of the area constitutes a basin of interior drainage. In such conditions the dominance of river erosion and marine sedimentation disappears entirely. The local investigator becomes impressed by the special problems of arid erosion and epicontinental sedimentation.

Moreover, as a result of general aridity since the last epeirogenic movement, the lasting effects of previous peneplanation are more apparent and extensive than is the case in more "normal" environments. Also, late orogenic movements of any magnitude are confined to New Guinea, and do not affect continental Australia at all. Only small portions of the eastern fringe of the continent exhibit strong plication of rocks newer than the older Paleozoic. Throughout almost the whole of the western three-quarters of the continent rocks as old as Proterozoic are practically undisturbed and unaltered over extensive areas.

Somewhere about early Miocene there occurred an enormously protracted period of still-stand, resulting in peneplanation proceeding to a very advanced stage of development. So little dissection of this vast peneplain has supervened since that time that the processes and effects of peneplanation can be studied in this region more easily and completely, perhaps, than in any other part of the world known to the writer by description or inspection.

If, then, it had happened that the science of geology had been born and had developed in the Australian region, conditions of peneplanation, intermittent stream action and epicontinental sedimentation under arid conditions might have come to be regarded as "normal"; and river erosion and marine sedimentation as rather aberrant.

This preamble is necessary to justify the writer's entry into any debate on the origin of the pre-Cambrian banded iron deposits of the world.

GEOLOGIC ENVIRONMENT OF BANDED IRON DEPOSITS.

These iron deposits, although best known and most completely studied in the classic Lake Superior Region of the United States and Canada, are very widely distributed in almost every part of the world, including Western Australia. All of these deposits show a very marked similarity in content and structure, and there can be no question that a single mode of origin can explain them all; and, conversely, any explanation that fails to explain one occurrence cannot be correct for any of them.

As pointed out by Moore and Maynard (3, p. 526) "the conditions of formation of these banded formations must be peculiar to the pre-Cambrian era, since no deposits exactly similar have been formed in later eras although they were deposited *on every continent* (italics W. G. W.) in that era." It is with a view of suggesting one possible and unique combination of geological conditions, capable of providing within the limits of the Doctrine of Uniformity, the necessary environment for the development of all the characteristic features of these peculiar yet universal formations that this paper is written.

Previous Laboratory Results.—The laboratory investigations of Moore and Maynard, and of Gruner appear to demonstrate clearly the following facts:

1. Cold carbonated and oxygenated waters, approximating in composition to ordinary meteoric waters, are capable of dissolving large amounts of iron oxide and silica in colloidal form from natural basic rocks. The rocks used in the experiments were norite and diabase.

2. Solution is expedited and increased by fineness of subdivision of the rock materials acted on.

3. Time of contact increases solution to a marked extent.

4. Mixed hydrosols of iron oxide and silica, artificially prepared, tend to precipitate one another.

5. Addition of quite small amounts of certain *natural* solutions of organic matter stabilizes mixed hydrosols to such an extent that they are capable of existence in unprecipitated condition for periods sufficiently long to permit them to be transported for long distances in natural waters.

6. Naturally occurring bicarbonates of alkalies, calcium and magnesium, are ineffective precipitants of iron and silica hydrosols.

7. Electrolytes occurring in natural salt waters are more or less effective precipitants. Naturally occurring mixtures of such electrolytes, such as exist in the sea, are more effective precipitants than are the pure salts individually.

8. Concentration of either hydrosols or electrolytes favors precipitation, though precipitation occurs in the cases of solutions with concentrations similar to those encountered under natural conditions.

9. Mixed iron and silica hydrosols stabilized by organic matter exhibit differential precipitation of the iron oxide and of the silica when acted on by electrolytes of the composition and concentration of sea water. Iron is precipitated immediately. Silica is precipitated much more slowly and incompletely.

"Duricrust."—For many years the writer has been impressed by the ubiquitous presence over the larger part of the Australian

continent of a formation, varying in chemical composition in strict conformity with the character of the underlying bedrocks, but marked, through all its variations, by the unmistakable criteria of subaerial chemical deposition of the materials, almost entirely as colloids in the first place. To this formation he has given the name "duricrust" (7).

Where bedrocks are granitic or gneissic the duricrust is in the form of a rather irregular deposit of oölitic or pisolitic bauxite, with a high percentage of silica in amorphous form which renders the material unsuitable for use as an ore of aluminum.

The fact which is most important in the present discussion is that, when the country rocks are dominantly basic, as appears to be the case in most or all of the regions in which are developed banded iron formations, the duricrust approximates in composition to goethite.

Where bedrocks are argillaceous, the duricrust becomes dense porcellanite. Locally, precious opal is developed in this environment. Where sandstones constitute the subjacent formations the duricrust consists of intensely hardened and cemented "quartzites" owing to the deposition in the porous rocks of secondary silica, largely amorphous. In areas underlain by calcareous rocks the duricrust becomes a pisolitic "travertine."

Substratum.—In every instance, irrespective of its lithological character, the duricrust rests on a completely leached substratum composed of the most insoluble residues of the original bedrock. Commonly the leached substratum is soft or pulverulent. This association of a soft substratum covered by a hard capping provides a weak structure in denudation. The undercutting of the leached substratum, chiefly by wind action, results in the highly characteristic types of scenery universal throughout inland Australia, namely, flat-topped mesas with parabolically curved flanks.

Careful examination of the leached substratum always, within my experience, reveals at least traces of the structure of the parent bedrock. Thus, near Perth, Western Australia, the "ghosts" of basic dikes that cut through the granite can be detected as vertical bands slightly different in color and texture from

the white, slightly more quartzose clays resulting from the decomposition of the granite itself. These thoroughly leached clays are used extensively as fireclays. In other places in the same area thin bands of coarse muscovite pegmatite, incoherent and fragile in the weathered condition, can be traced from the granite through the leached substratum, into and through the duricrust without appreciable disturbance. In other parts of Australia quartz veins no thicker than a knife blade can be traced continuously from the slate bedrock to the surface. Such fragile units could not possibly withstand the slightest trace of mechanical force. Any suggestion of mechanical transportation is eliminated and the observed phenomena prove conclusively that the superficial hard capping and the subjacent substratum which together form the duricrust must have been developed essentially *in situ*.

Formation of Duricrust.—The writer has developed this thesis in a few papers (6–11), in publications unlikely to reach the notice of workers in other countries. He would, therefore, venture to suggest some consideration of the tentative theory now advanced, since it does appear to explain all the anomalous features so clearly brought out in contributions to ECONOMIC GEOLOGY, and especially in the epoch-making paper of Moore and Maynard (3).

In his original publication the writer suggested that several factors, all anomalous from the point of view of what is usually accepted as normal in dynamic geology, have functioned in the development of the duricrust. These include an advanced stage of development of peneplanation, intrinsically low rainfall, and markedly intermittent incidence in its precipitation.

Until a very advanced stage of base-leveling has been attained, the rain precipitated on a continental area is largely discharged through streams to the sea. A certain proportion of the rainfall passes through soil and subsoil by percolation, decomposing the original rock-forming minerals and dissolving the soluble constituents of them en route. In these conditions, though chemical weathering is functional and considerable loads of dissolved matter are carried by the flowing streams, mechanical erosion and

transportation of fragmental material are the dominant activities, and normal sedimentation, chiefly in the sea, is the outstanding result.

When peneplanation of a continental area is pushed to its ultimate limit of completeness, the whole land surface is reduced to the condition of a nearly featureless plain rising gradually inland to insignificant elevations above base level—the sea. In this condition stream gradients are reduced to ineffective values; run-off of water becomes exceedingly sluggish; stagnation is widespread; mechanical transportation is practically non-existent and can move solid material only in the finest state of subdivision; percolation and sub-surface seepage gradually dispose of the bulk of the rainfall; long contact is assured between the materials of the subsoil and meteoric waters charged with oxygen, carbonic acid and, in suitable environments abundant dissolved organic matter; chemical weathering and transportation of materials in solution or pseudo-solution become the dominant geological process.

At the time of his description of the "duricrust" the writer's appreciation of the chemical processes involved was inadequate to enable him to provide anything like a complete account. The masterly work of Moore and Maynard has supplied the deficiency, and has inspired complete confidence in the general accuracy of the views then advanced. The conditions postulated above for complete peneplanation are exactly those that provide optimum environment for the production of cold natural solutions of the type investigated by these authors, and for such fluids to perform their work of dissolving rock-forming minerals and transporting the resultant products.

In his original essay the writer made the further suggestion that a factor in the development of the duricrust, scarcely less important than perfection of peneplanation, was that of markedly seasonal distribution of rainfall. This condition is very conspicuous in Australia at the present time, and is likely to have been persistent throughout Neozoic time, since there appears to have been little change in geographic environment in the southern and western portions of the continent during that interval.

During wet seasons, which may be annual in some areas but distributed over longer cycles in the more arid sectors, relatively heavy rainfall provided meteoric waters for percolation. These waters sink through the porous soil into the finely divided subsoil. Moore and Maynard (3, p. 276) emphasize the fact that fineness of subdivision of mineral matter and also time of contact exert a powerful influence on the solution of rock minerals by waters of meteoric type.

After a longer or shorter period of saturation of the subsoil the solutions are drawn to the surface by capillarity as the soil becomes desiccated during the dry cycle. The solutions, as shown by Moore and Maynard, are essentially hydrosols of iron oxide, alumina and silica stabilized by organic colloids. They should contain also salts of sodium, potassium, calcium and magnesium, probably chiefly bicarbonates, which, as shown in the paper referred to, are not very effective precipitants of the colloids at the concentrations involved. The solutions and hydrosols are rapidly evaporated at and close to the surface, and precipitation of their contents takes place with or without the assistance of bacterial or other low forms of life. Seasonal repetition of the process removes all the more soluble materials including the whole of the sodium and potassium salts. Material of intermediate solubility, such as calcium and magnesium carbonates persists temporarily and in reduced amounts. In Australia, the persistence of the slightly magnesic but essentially calcareous nodular " travertine " encountered over calcareous bedrocks is very limited. In all but favourable situations almost the whole of this type of duricrust is completely removed.

Those constituents of the soil solutions which are transported as hydrosols are precipitated seasonally in stable form. Their mode of deposition favors concretionary habit, and explains the ubiquity of oölitic and pisolitic structures.

The final result is the development of a hard superficial concretionary crust consisting essentially of silica, ferric oxide or alumina, or mixtures of these in varying proportions, resting on a substratum from which has been removed all constituents capable

of being brought into solution by carbonated and oxygenated meteoric waters. The completeness of leaching is indicated not only by the color of this residue, but by the availability of the clays as very refractory fireclays.

Such a method of formation appears to account satisfactorily for the duricrust of Australia, and also for some other formations such, for instance, as the concretionary iron-stones of Uganda in Africa (4). The suggestion may be advanced also that at least some of the world's principal bauxite deposits, underlain by rocks of syenitic facies, may have originated in the same way. These appear, from description, to differ from the so-called laterite of Western Australia only in their lower silica content, a fact readily attributable to the difference in composition between syenite and the granitic rock that underlies the laterite.

Even with the highest degree of perfection of peneplanation the ultimate erosion surface is *nearly* a plain, but not quite. There are mild residual differences of level that must give rise to the development of sluggish, tortuous streams during periods of relatively copious rainfall. Torrential rain must produce sheet floods; but, even on such occasions, strong currents are improbable owing to the lowness of the gradient. Only very locally and exceptionally can beds of conglomerate and sandstone be produced, probably at long intervals, in local depressions. The only type of mechanical sedimentation that can be expected is in the form of fine textured mud and silt. Even this is quite subordinate in amount. The dominant load of the slowly moving waters is that in solution, consisting essentially of hydrosols of the types described by Moore and Maynard.

In the development of the duricrust seasonal incidence of rainfall is insisted on. As shown above, this factor favors deposition *in situ* of the hydrosols immediately on reaching the surface. In areas where precipitation, whether intrinsically light or heavy, is well distributed in point of time it is likely that duricrust will not be produced. The whole of the hydrosols will be transported by the sluggish streams until they reach depressions on the continental surface. Moore and Maynard have shown that, in presence of

suitable organic colloids, even mixed hydrosols are stabilized to such an extent that they are capable of long-distance transportation. This is not the case with ferrous salts of inorganic acids which are rapidly oxidized and precipitated. Ultimate precipitation of the hydrosols may be brought about by evaporation of the solvent, by the action of electrolytes, by organic (notably bacterial) action, or by a combination of these.

Formation of Banded Iron Ores.—Moore and Maynard have mentioned in passing the possible influence of peneplanation and of a certain amount of sedimentation in epicontinental basins; but appear to have passed over this possibility without exhaustive investigation of its corollaries. I maintain that, under the conditions postulated, not only is it most probable that such epicontinental sedimentation is dominant but that it automatically provides such an environment as to explain many if not all of the phenomena still regarded by Moore, Maynard and others as obscure and puzzling.

These authors emphasize the differences between the highly siliceous, markedly banded iron formations of the older pre-Cambrian and the less siliceous, less banded, obviously sedimentary iron deposits of later pre-Cambrian, and also the less siliceous, non-banded Paleozoic and Mesozoic marine formations in Newfoundland, the eastern United States, England and France. One of the clues lies, it appears to the writer, in the fact recorded by them, namely, the markedly lower silica content of the later formations as well as the absence of distinctive banding. The full implication of these facts does not appear to have been appreciated. Their experimental work proves conclusively the paramount importance of time in the processes of precipitation of the colloids, and also the striking features of differential precipitation of silica and iron as regards time. If the solution of the mixed colloids is emptied into the sea, as should be the case with self-respecting "normal" discharge, differential precipitation of the iron and silica supervenes. The iron is thrown down almost immediately; while, as indicated by the laboratory results, the silica does not begin to be precipitated for hours, days or even weeks, but does come down eventually in lightly flocculent form.

In the open ocean quiescence is never complete; tidal and other currents are always present. In such conditions, both before and after precipitation, the silica must be carried away from the locus of precipitation of the iron. Marine deposition of banded iron and silica deposits is highly improbable. Even apart from oceanic or tidal drifts, currents of sufficient strength to bring about the emplacement of the iron solutions would themselves be competent to carry to greater distances the silica solutions or flocculent precipitates, and to ensure their dispersion and suppression as an independent sedimentary unit. The association of non-banded, low-silica iron deposits with certain types of marine sediments is, however, exactly what should be expected.

The postulated conditions of ideally perfect peneplanation provide, without making undue demands on credulity, an ideal environment for the "highly banded formations of the Keewatin, which are much more restricted in size and much more numerous" (3, p. 525) than are the less siliceous, "marine" deposits of the Animikian, Paleozoic and Mesozoic referred to above.

The hypothetical peneplain surface possesses numerous isolated depressions providing "sinks" within which quiet and unhurried precipitation of the colloids can proceed undisturbed by currents, and without admixture of excessive mechanically-formed sediment. Banding is easily explained as due to successive accessions of solution readily accounted for by seasonal, but not necessarily annual cycles of rainfall. It is stated (3, p. 519) "There is no doubt that banded silica and iron can be formed in nature by this process (successive additions of mixed colloids to a suitable solution of electrolytes: parenthesis W. G. W) provided a periodic supply of silica and iron is available." Seasonal influx of duricrustal solutions does not strain credulity. Successive periods of agitation and quiescence (3, p. 518) do not appear to be called for; the simple lag in the differential precipitation of iron and silica is quite adequate to produce the banding. Only in their repeated insistence on deposition in the sea do Moore and Maynard appear to be at fault.

Nor are there lacking under the postulated conditions ideal chemical environments to effect precipitation. Analogy with existing conditions in Australia suggests that, in many of the base-leveled areas, the climate may have been arid. In such circumstances the combination of concentration of salts through evaporation of surface waters, and the accession of cyclical salts from the sea leads to the accumulation in epicontinental depressions of salt lakes and saline deposits. Such reaction basins, if present, would be ideal for quiet electrolytic precipitation of the mixed hydrosols.

Of all the theories summarized by Moore and Maynard that of Gruner approaches very nearly to the one here advanced. He emphasizes the climatic factor; but is, I think, mistaken in demanding a tropical or subtropical wet climate. He does not take seriously into account the possibility of peneplanation; and, in common with practically all American geologists, visualizes the sea as the chief or only repository.

Gill suggests that precipitation was due to the mingling of solutions from different sources. Such a supposition is neither necessary nor probable if the sea is the locus of precipitation as he quite definitely visualizes. In the first place, the marine salts themselves have been demonstrated to be highly efficient precipitating agents. In the second place, appropriate solutions from different sources would have considerable difficulty in locating one another in the sea's immensity.

Incidentally, in reference to the very general insistence on deposition in the sea it may be pointed out that, except in the case of phenomenally voluminous rivers, it is rare for actual river waters to reach the sea itself. Far more commonly it happens that, well upstream within river estuaries, the salinity of the waters already approximates to that of the sea. Would it not, then, be more usual for hydrosols carried by rivers to be associated with estuarine rather than with truly marine deposits? The criteria of distinction, especially in the case of ancient deposits, are by no means so indubitable as to make it certain that such an association is not, in fact, the more usual one; particularly since, in all prob-

ability, the idea of such an association has not entered the minds of field investigators, and no critical search for specific criteria has been made. Only when rivers empty into tideless seas ("barred basins") is it likely that the associated sediments would be truly marine: and even in such cases evidences of some peculiarity of conditions might be forthcoming if specifically looked for.

The oölitic and pisolitic habit of most of the varieties of duricrust, particularly of its ferruginous and aluminous members, suggests an analogy with the structures referred to by Moore and Maynard, particularly in reference to the Paleozoic and Mesozoic deposits. It is probable, however, that this analogy is misleading. The duricrust is a subaerial deposit, while the particular iron deposits referred to are shown to be associated with marine sediments. It seems probable that the colloidal form of the precipitate may have an influence in favoring the concretionary habit, with or without the influence of organisms. This, however, is not stressed in the case of marine deposits. Such a concretionary development is highly probable in basin deposits that are desiccated intermittently during dry seasons. In such circumstances successive coatings of colloidal oxide material would be added to existing nuclei.

There is a decided possibility that direct duricrustal development would be competent to produce certain types of iron deposit. The writer was inclined to advocate such a mode of origin for many of the deposits that he has examined or descriptions of which he has read. On more mature consideration, however, it appears more probable that deposits of such a type would be relatively impure. Transport in solution and selective and differential precipitation of iron oxide and silica appear to explain much more satisfactorily both composition and banding of the deposits here specially considered.

Other Explanations.—Without venturing to gainsay the opinions of such leaders as Van Hise and Leith, the writer is completely convinced by the arguments of Gruner that recourse to hot magmatic solutions is unnecessary to account for the iron and

silica solutions in the case of most or all of the banded iron formations. Moore and Maynard have proved conclusively that hydrosols of apropriate type can be produced from basic igneous rocks by cold carbonated and oxygenated waters under laboratory conditions closely simulating natural ones. The fact that abundant basic rocks are present in the areas that yielded the iron and silica provides an abundant supply of suitable raw material for the natural processes involved.

The authors of most of the theories involving the action of heated waters appear to be influenced, in part at least, by a necessity to explain the magnitude of the phenomena (the enormous bulk of the deposits) by the powerful nature of the causative reactions. Stupendous results require stupendous causes: but in this case it would appear that the stupendousness is that of the time element. Moore and Maynard have shown that perfectly ordinary cold natural solutions, in sufficient volume and operating for a sufficiently long period, are quantitatively adequate to achieve the observed results.

That magmatic waters are responsible for the formation of many major bodies of iron ore admits of no doubt; but such occurrences should and do exhibit all the criteria of metasomatism and metamorphism of the older rocks with which they are associated.

Were deposition of iron and silica by magmatic waters directly derived from basic volcanic rocks the normal mode of origin of such formations, surely one would expect deposits of the type under discussion to be the regular associates of such basic lavas, if not everywhere and at all times at least with sufficient frequency to demonstrate the normality of the association. The Doctrine of Uniformity cannot be invoked to account for a unique occurrence by methods that cannot be explained by appeal to actual examples, unless some plausible reason for the singularity can be adduced.

The suggestion advanced by Collins, Quirke and Thomson that the deposits were formed by ascending, heated mineral waters spreading out in depressions, precipitation being effected by cooling and evaporation of the solvent, and that the observed banding

is due to conveniently recurring repetitions of the ascent of such waters, appears rather improbable. Neither the type of extravasation required (which should be fairly common in volcanic regions or other igneous areas) nor the conveniently spaced periodicity of the phenomena is supported by adequate geological analogy or fundamental reasoning.

Further, the solutions derivable from such magmatic sources are not those that would be likely to generate the amorphous and banded precipitates of the type under discussion. The experiments of Moore and Maynard are eminently satisfying in this direction. They appear to have proved adequately the plausibility of every stage of the process, from solution, through transportation to selective and differential precipitation. Only in the aspect of emplacement and environment do their conclusions appear to be inadequate.

The notorious instability of ferrous salts of mineral acids in natural waters has been made abundantly clear by Gruner and Gill. Such salts are decomposed and precipitated immediately on exposure to the atmosphere, and their deposits are localized at the points of emergence of the spring waters carrying them. Again, strict application of the Doctrine of Uniformity fails to supply proof of the type of transportation of such salts that would be required to account for the emplacement of the banded deposits. Iron and silica deposits of spring origin are enormously abundant, but they do not exhibit characteristics remotely resembling those of the pre-Cambrian banded iron deposits. The hot spring deposits that the writer has seen in Yellowstone Park and New Zealand offer no suggestion of close analogy with the banded iron deposits he has examined in Western Australia.

Still less plausible appear to be the suggestions of origin from submarine hot springs. Not only are unequivocal examples of this type lacking, but the chemistry, physics and mechanics of the process make excessive demands on credulity. Moore and Maynard give chapter and verse for every fact of solution, transportation and precipitation of iron and silica hydrosols stabilized by organic matter. Hot spring solutions would almost certainly

consist of salts, chiefly ferrous, of silicic, sulphuric and hydrochloric, and possibly carbonic acids. Is there any laboratory or other evidence to show that selective precipitation of the iron and silica from such solutions, competent to produce banded amorphous deposits, is a necessary corollary of their admixture with sea water?

Change of temperature caused by the mingling of such solutions at the point of contact between them and the waters of the sea might be effective in causing some kind of mutual decomposition and precipitation; but it seems far more probable, and, at all events not proven, that such precipitates would remotely resemble those which have given rise to the banded iron formations.

It seems far more reasonable to suppose that the rapid dilution of the emergent solutions by the enormous body of sea water into which they are discharged, aided as it would certainly be by violent ebullition, temperature effects and differential density, would favor dispersion rather than concentration of the solutes.

Similar arguments apply with even greater force to suggestions of interaction between hot basic lavas and sea water. No such effects resulted from the enormous floods of basalt that poured into the sea during the long continued eruptions in Savaii, Samoa. Submarine basic lavas have been extremely common throughout geological time; but such lavas are neither universally nor usually accompanied by banded silica and iron deposits.

Some consideration should, I think, be given to the admissibility of laboratory evidence in problems of this type. Unquestionably such experiments, if carried out with due regard to naturally occurring conditions, must supply valuable data. The qualification mentioned, however, is exceedingly difficult of attainment in practice: and even when every effort has been made to secure completeness and meticulous accuracy, lingering doubts must remain. Laboratory experiments are strictly controlled as to conditions of environment, and represent rather ideal than natural combinations. In nature there are all sorts of accidental factors, the effects of which may or may not be of dominating importance. Thus, natural variations in temperature, barometric pressure, il-

lumination, dilution, specific types of dust or sediment, natural catalysts, specific organisms, and a host of others, many of which may be entirely overlooked, all apparently insignificant, may actually constitute nature's way of "doing the job." The curious fact noted in their experiments by Moore and Maynard (3, p. 507) that the natural admixture of salts present in sea water is a far more effective precipitant than are any of the single salts individually at similar concentrations is an illustration of this.

Only insofar as laboratory experiments run strictly parallel as regards their results with natural phenomena can they be adduced as positive evidence. Failure of a laboratory set up to reproduce nature's results cannot be accepted as a definite disproof of the possibility of a given reaction in nature; but only as a proof that, under the conditions of the laboratory set up, the particular reaction is inadequate to explain the natural phenomenon. It is obvious that variations in the selected environment explain the otherwise extraordinary diversities and contradictions in the results obtained by many thoroughly competent investigators. Examples of this kind of thing are summarized by Moore and Maynard in pages 365 *et seq.* of their paper.

Especially impossible of imitation in the laboratory is one factor of illimitable availability in nature, namely time. Rarely indeed do laboratory experiments extend beyond days in their duration. Experiments extending over years are very uncommon. The longer an experiment continues within the laboratory the greater is the possibility that it may fail to reproduce some of the essential variations that are part of nature's scheme.

Failure to obtain a positive result from a given experiment may indicate that the particular reaction has not taken place within the time limit of the experiment. On the other hand it may be due to the fact that the technique employed is not sufficiently sensitive to detect small initial quantities of the products of reaction. Few chemical tests applicable to complex colloidal and organic substances can compare in sensitiveness with the measurements available in radioactivity or spectroscopy, for instance.

The astonishing agreement, then, between observed facts and the laboratory results of Moore and Maynard is all the more convincing, and should unquestionably receive the most serious consideration. If any comment may be permitted it is to the effect that the work on silica appears to be rather more artificial and theoretical than that on iron colloids.

Another risk arising from highly suggestive laboratory work may be mentioned: namely, the attainment of results that at first sight appear to provide complete analogies, but which, on closer and more detailed investigation turn out to be mere superficial resemblances. The writer can remember the enthusiasm of petrologists during the "nineties" over the application of the "Soret principle" to magmatic differentiation. The quantitative inadequacy of the principle was later proved conclusively. In relation to the present discussion Moore and Maynard have shown, conclusively I consider, that the fascinatingly simple Liesegang effect is inadequate to explain the banding of the iron ores. They have substituted, without perhaps appreciating fully some of the implications thereof, the differential precipitation of iron and silica colloids by electrolytes of marine type and origin.

Still another possibility of misconception is suggested by the admirable paper which forms the basis of the present discussion, namely, the acceptance of *averages* derived from widely dispersed investigations. This is illustrated by the use made of the monumental work collated by Clarke in his Data of Geochemistry. The *average* content in silica and iron of the rivers of the world is used tacitly as the foundation for the main thesis advanced. If there is anything in the contention advanced by the present writer that the deposits in question were formed under highly specialized (not necessarily abnormal) conditions such data lose much of their value. The vast majority of the analyses used in calculating the *average* have been made on water obtained from flowing streams or from lakes along river sources. In the majority of instances the climatic, seasonal and meteorological conditions prevailing at the time when the samples were collected have not been recorded. The record, however, is so extensive that there is a reasonable

probability that seasonal and other periodic variations have cancelled out, and that the average is a fair one for flowing streams.

It is the writer's contention, however, that, under the conditions postulated, the drainage of the area is of a type quite different from that exemplified by the world's flowing rivers and their lacustrine expansions. Under the intensely base-leveled conditions visualized, drainage is not only excessively sluggish, but the factors making for excessive solution of rock material are preternaturally high. If this is correct it is the maxima, only, from Clarke's tables which should be utilized, and not the averages.

As a case in point, the value quoted from Simpson (5) for a stream in Western Australia probably approximates far more closely to the norm for duricrustal formation than do ordinary river waters. Though the conditions in the part of Western Australia from which Simpson's sample was collected are no longer those of advanced peneplanation, the general environment is much nearer that postulated in this discussion than are the basins of constantly flowing streams. The stream mentioned by Simpson is intermittent in its discharge.

High concentration of the hydrosols greatly favors precipitation by marine electrolytes (3, p. 282). Specially high concentration should prevail under duricrustal conditions.

Organic Matter.—In regard to the possibility of the presence of large amounts of organic matter in pre-Cambrian time the writer has nothing material to add to the complete discussion of the question given by Moore and Maynard. Again, however, strict application of the Doctrine of Uniformity appears to favor the assumption that such organic matter could have been present. In spite of great oscillations the tempo of evolution since Cambrian time is well recognized. The earliest known floras and faunas are already high in the evolutionary column. It would be entirely unreasonable to assume that, because we cannot actually study the fossils, the tempo of evolution suddenly slowed down when the oldest known fossiliferous formations were deposited. The well established fact that land floras and faunas have less chance of preservation than have marine organisms rather supports any

claim for the possible existence of early land floras. The strong possibility that the earliest forms of life were of lowly organization also militates strongly against the probability of their leaving any recognizable traces of their existence.

Although not essential to the argument, the possibility of bacterial participation in the precipitation of colloids has been fully traversed by Moore and Maynard. If there is anything in the suggestion that the chief loci of precipitation were in the form of stagnant epicontinental basins optimum conditions for bacterial development are indicated. If, however, the waters in the basins were non-permanent and highly saline this possibility is reduced, though not necessarily eliminated. Even in saturated brines like those of the " salins " of the South of France and of the salt lakes of Central Australia the waters and precipitated salt are colored pink or red by the enormously prolific red bacteria that live in such solutions. Personally, the writer favors precipitation by electrolytes as the more probable process.

Still another implication of the suggestion here put forward is worthy of some consideration.

Many writers have remarked on the uniqueness of deposits of the banded iron type, and their limitation to the pre-Cambrian formations. These facts call for the development of specialized conditions at one period; never repeated, in exactly the same form and to exactly the same degree at all events, in any subsequent period of earth history.

It seems clear that after uplift has initiated a new geographic cycle the early stages of dissection of a land surface are, geologically speaking, of extreme rapidity. As maturity of erosion develops the process slows down progressively. The latest stages of base-leveling, when the relief of the land surface has well nigh disappeared and when mechanical erosion and transportation have become feeble in the extreme, must be almost inconceivably protracted.

Owing to the constant redevelopment of diastrophic stress within the earth's mass it can rarely happen that the earth's crust, even in any one sector, can remain stable for a period sufficiently

long to permit of attainment of ideally perfect peneplanation. Still less is it probable that such ideal perfection of peneplanation of world-wide extent could have been frequently repeated. The evidence even suggests that, once only, when the world was young, did this state of things exist. Since that time even local perfection of peneplanation, although in many places reaching advanced maturity, has not attained to the extreme limit of development.

It is not the writer's intention to pursue, here, certain possible and probable consequences of perfection of peneplanation in controlling certain other types of sedimentary deposits. At the moment it may be pointed out that certain logical deductions from the hypothesis suggest that the development of "barred basins" (10) on and around the circumference of a completely base-leveled continental area is an almost inevitable corollary. The writer has suggested that basins so formed may, in fact, must exhibit "euxinic" features that are favorable to the deposition of sediments poor in oxygen and rich in organic matter and sulphur, capable of providing the mother rocks of petroleum deposits. Curiously enough glauconite appears to be one of the deposits characteristic of barred basins. Its analogy, suggested by Gill, with the iron silicates associated with banded iron deposits may be more than a coincidence.

What may have direct application in the present discussion is that such deposits are very rich in iron sulphide. This appears likely to be one source of the "brass" (of the miners) commonly met with in coal seams. May it not also provide some of the pyrite that is recorded (3, p. 526) in certain iron ore deposits.

Although it may be possible in this way to account for some anomalous iron ore deposits containing pyrite without recourse to hot solutions, the writer would be the last to advocate one unique mode of formation for all, or even the majority of such deposits. He contends very strongly for a magmatic origin (or perhaps better sub-magmatic—as indicating the possibility of some intermediate process) for numerous Australian iron deposits that he has examined in detail during the past three years. In widely separated deposits throughout the length and breadth of Aus-

tralia the dominance of metasomatic processes is manifest. The evidence is clear in the majority of cases that the iron solutions have been derived, mostly rather indirectly, from ultimate magmatic sources.

No attempt is made here to provide a bibliography of the subject dealt with. Moore and Maynard have summarized this literature so completely that, though he has studied most of the original papers referred to, the writer has been content to quote them second-hand from this source. Although the writer has only limited access to technical publications he has, so far as opportunity offered, studied in the original many of the published descriptions, including many in Russian, Swedish and Portuguese, and has endeavoured to assimilate the main principles. Naturally, however, the theme of the present contribution is suggested by and founded on the outstanding reports that have appeared in the official publications of the United States and Canadian Geological Surveys, and particularly the magnificent suite of papers on the subject appearing during the last twenty-five years or so in the pages of ECONOMIC GEOLOGY. It is to these American and Canadian authors that he acknowledges his boundless debt of gratitude.

GEOLOGICAL ADVISER,
COMMONWEALTH OF AUSTRALIA,
CANBERRA F. C. T.,
Dec. 10, 1940.

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ARTESIAN CONDITIONS IN THE LOWER TENNESSEE VALLEY.

ROGER RHOADES.

ABSTRACT.

The lower Tennessee River flows in a broad valley deeply underlain by fluviatile sediments. The flanking highlands possess only moderate elevation.

Ground water migrating from the highlands toward the river enters confined aquifers and artesian effects occurs in, (1) the deeply buried bedrock, and (2) the superjacent flood plain sediments, these two aquifers possessing artesian pressures which, while related, differ in magnitude and manner of development. The causes of these artesian conditions are lithologic and arise from the normal river sedimentation; for this reason it is probable that similar artesian phenomena are more common than has previously been realized, and may exist in the lower reaches of many large rivers. It is known that the conditions responsible for the artesian effects in the lower Tennessee Valley are duplicated in the adjacent parts of the lower valleys of the Cumberland and Ohio rivers.

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INTRODUCTION.

PRELIMINARY investigations of dam sites on the lower Tennessee River by the Tennessee Valley Authority covered an area that included adjacent parts of the lower Cumberland and Ohio valleys. A site located on the Tennessee River, 22.3 miles from its mouth, was chosen for the construction of Kentucky Dam (Fig. 1). After the selection of this site, but prior to construction, comprehensive exploration involved many procedures that clarified the hydrology of the region, and disclosed artesian conditions arising from simple geological causes that undoubtedly exist commonly in the valleys of many large rivers.

The interpretation of ground water conditions is important in the consideration of the feasibility, optimum design, and method of construction of almost all engineering works but it is especially significant in connection with dams. Although the function of a dam is mainly to control surface water, the control of the underground extentions of the reservoir is an accompanying problem of equal importance but one which frequently is more difficult to elucidate and solve.

In regions of deep alluviation the underlying foundation materials are generally highly pervious, a condition that emphasizes the importance of interpretive ground water studies. In dams located in such environments, the design, safety, and efficiency of the structure are strongly influenced by considerations related to: (1) possible underflow beneath the structure—with or without damaging abstraction of foundation material, (2) permeability of the abutments and the reservoir rim, (3) necessity for and type of cut-off structures, (4) the existence of interconnecting openings in the underlying bedrock and the ease of water transmission through them, (5) the possibility of hydraulically produced uplift pressures, and many other major and minor considerations. During construction, efficiency, safety and economy depend to varying degrees upon proper control of the ground water and the correct interpretation and anticipation of the hydraulic conditions to be encountered in erecting cofferdams, unwatering excavations and

treating cavernous portions of the foundation with grout or by other means.

In spite of the importance of ground water interpretation in connection with engineering operations, conditions of artesian pressure such as exist on the lower Tennessee River have generally been interpreted in terms of an ideal water-table of free surface, or have been passed over without specific explanation.

METHODS OF INVESTIGATION.

Over 800 exploratory borings, aggregating in excess of 100,000 feet of drilling, were made at Kentucky Dam site with core-drills.[1] Water-table measurements were made in the borings as they were being put down and casing was left in many of the holes to permit continued observation of the water levels. In addition, observations were made of the wells in the neighborhood, and the fluctuations of the river level were closely noted. On the basis of these observations, " water surface " profiles were drawn.

Numerous test-pits were excavated in the flood plains and on the highlands that form the reservoir rim. Pumping tests were made in pits that penetrated the saturated materials of flood plains. The operations at test-pit No. 8, located on the flood plain, 1350 feet west of the river, are illustrative of the procedures followed. This pit was sampled at intervals of two feet and the excavation was under continuous geological scrutiny. As the excavation encountered lithologic changes, pumping tests were made. The pit was ringed with successive circles of observation wells and from these the cone of water-table depression was deduced as water was pumped from the pit at a measured rate, the draw-down being simultaneously noted. From these observations the velocities of inflow into the pit were calculated and correlated with the materials that were permitting the inflow.

Similar tests were made in test-pits which, because of their location on high ground or because of their shallow depths, did not penetrate saturated materials, but in such cases it was neces-

[1] Lynn, A. V. and Rhoades, R. F.: Foundation exploration at Kentucky dam site. Eng. News-Record, 125: 70–73, 1940.

sary to pump water into the pit in order to determine the rate of outflow. The quantities of water available for pumping into these dry test-pits seldom permitted accurate evaluation of the cone of influence in the surrounding area and these tests, therefore, lacked the refinement of those in saturated materials.

The program of test-pitting was culminated by the construction of a shaft 90 feet deep and 20 feet in diameter, made up of a ring of sheet piling from within which the alluvial sediments were excavated to expose the bedrock surface. The investigation of ground water behavior was one of several objectives of the construction of this shaft and informative observations were made until the inflow of ground water and sand so impeded the operations that it was necessary to freeze [2] the sediments.

Velocities of percolation through clayey surface sediments above the zone of saturation were measured by means of a special test. Metal standpipes, several feet high and from 42 to 54 inches in diameter, were embedded in the clay and filled with water. A small tunnel was dug beneath each standpipe in such a way that a section of clay about three feet thick intervened between the ground surface inside the standpipe and the roof of the tunnel. The tunnel was then filled with coarse gravel to prevent slumping of the clay. Water from the standpipe eventually seeped through the three-foot section of clay and into the drainage tunnel below. The amount of water escaping in this way was measured in the standpipe, allowance being made for evaporation. These tests were conducted for several periods of twenty-four hours at different localities, and the velocities of percolation were calculated.

Permeability determinations of many samples were made in the Soils Laboratory. Permeability values used in the following discussions, however, are those derived from tests made in the field on materials " in place."

Fluorescein dye and electrical methods of observation were occasionally used experimentally or as corroborative auxiliary tools in connection with other procedures.

[2] Goodenough, B. W. and Rhoades, R. F.: Freezing aids shaft excavation. Comp. Air Mag. 44: 5778–5782, 1939.

Several hundred auger borings were drilled to determine the areal extent, thickness and continuity of the clayey sediments that mantle the topography.

TOPOGRAPHY.

The valley of the lower Tennessee River varies from 6,000 to 10,000 feet wide and is about 8,000 feet wide at Kentucky Dam site. The river averages 1,500 feet in width, being flanked by flood plains which, at this locality, are broadest to the west of the river.

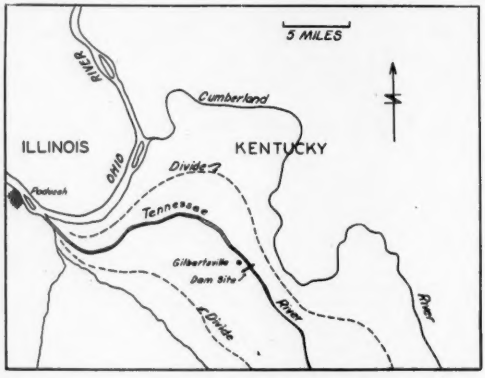

FIG. 1. Location map showing drainage area of Lower Tennessee River.

These flood plain surfaces exist at two levels: the present or "active" plain at 320 to 325 feet above sea level, and a higher surface ("second bottoms") at 340 to 350 feet above sea level which is inundated only at times of excessive floods. At Kentucky Dam site this higher surface occurs only to the west of the river (Fig. 2). The normal level of the Tennessee River at this point is 302 feet above sea level.

The highlands bordering the river rise to about 400 feet above sea level (100 feet above the river) at the margins of the valley and to slightly higher positions at points farther from the river. The Tennessee-Cumberland River divide lies one mile to the east

of the Tennessee River and the Tennessee-Clark's River divide lies seven miles to the west (Fig. 1).

GEOLOGIC CONDITIONS.[3]

The bedrock in the vicinity of Kentucky Dam site consists of lower and middle Mississippian limestones of the Ft. Payne, Warsaw and St. Louis formations. The Ft. Payne formation, a very siliceous limestone with numerous lenses and nodules of chert, is the prevailing bedrock formation immediately at the site. It attains a thickness of 600 feet and is underlain by sixty feet of cherty limestone and calcareous shale of the Ridgetop formation beneath which lies the Chattanooga shale at a depth of about three hundred feet below sea level. These formations are almost horizontal and undeformed.

The Ft. Payne formation (65 per cent $CaCO_3$) is less soluble than most limestones but solution cavities are nevertheless common and in places are extensive. These cavities form continuous conduits for the passage of ground water, but they are circuitous and possess local constrictions or are partially filled with the clayey residuum of the dissolved limestone. Vertical members of this lattice lead upward to the bedrock surface, and are generally filled with infiltered sediment and residual clay.

The lower reaches of the Tennessee River and the adjacent parts of the Ohio and Cumberland rivers formerly occupied deep valleys cut into bedrock,[4] and which later became filled with alluvium to a maximum depth of 120 feet (Fig. 2). Scattered bedrock outcrops lie at the outer margins of the flood plains but, between the valley sides, the rock surface forms a broad trough, that lies about 230 feet above sea level.

The river sediments (exclusive of the flood plain clays) are alternations of sand, gravel and clay, or mixtures of these materials. They are poorly sorted and individual zones and layers are lens-like and discontinuous.

[3] Eckel, E. C. and Staff: Engineering geology of the Tennessee River system (Rhoades, R. F., Geology of the Kentucky Project). T. V. A., Tech. Mon. No. 47.

[4] Rhoades, R. F.: Profiles of the buried valleys of the Ohio, Cumberland and Tennessee Rivers (abstract). G. S. A. Proc. for 1936 (1937), p. 97.

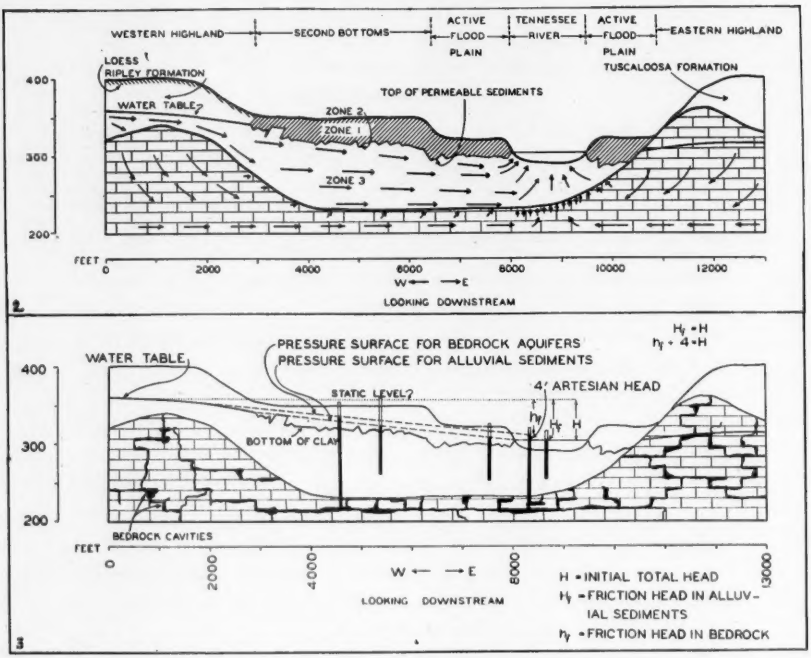

FIG. 2. Generalized topographic and geologic conditions at Kentucky Dam site (with schematic representation of ground water flow from highlands to river).

FIG. 3. Pressure surfaces beneath river and west flood plain.

In vertical section the sediments are divisible into three zones (Fig. 2). The flood plains are invariably mantled with recently deposited, silty, gritty, brown clay of limited permeability, and from 10 to 30 feet thick (Zone 1).

The greater part of the section of fluviatile valley-fill consists of sand and gravel (Zone 3). These are coarsest in the lowest layers where they contain cobbles up to ten inches in diameter.

Immediately beneath the flood-plain clay are sandy clay and clayey sand (Zone 2) which, from the standpoint of permeability,

are intermediate between the clay, above, and the sand and gravel, below. This zone is absent in places but is commonly present and conspicuous. The thickness is variable but averages about 15 feet. The transition into the overlying clay of Zone 1 is gradational but the lithology generally changes abruptly at the boundary of Zone 3.

The narrow, eastern flood plain surface is underlain by bedrock which, although sloping toward the axis of the buried trough, is not deeply buried. In that locality, the clay of Zone 1 extends downward to near the bedrock surface, the sandy clay of Zone 2 is thin, and sand and gravel of Zone 3 are absent except at points farther from the valley sides and closer to the present river where the rock surface has descended toward the depths of the buried channel.

The velocities of percolation through the sediments of Zone 2 and Zone 3 were determined by means of pumping tests at test-pits. In test-pit No. 8 the zones of sediments had the following dimensions: from the ground surface at elevation 319.6 to elevation 305.6, clay of Zone 1; from 305.6 to 289.1, sandy clay of Zone 2; from 289.1 to the bottom of the hole (bedrock) at elevation 229.1, sand and gravel of Zone 3, the coarsest part of which lay immediately on the bedrock surface. The velocities of percolation through the clays of Zone 1, which lies above the zone of saturation, were determined from standpipe tests at various points in the general locality of the dam site. The following velocities of percolation were obtained:

Zone 1 (various standpipe tests)	0.001 to 0.0006 feet per minute at *unity gradient*.[5]
Zone 2 (test-pit No. 8)	0.06 foot per minute at *unity gradient*.[6]

[5] Velocities quoted are actual linear velocities of water through the pore-spaces of the sediments (assuming a porosity of 34 per cent), mathematically reduced to a gradient of 45 degrees, which would result from a unit pressure head causing a flow through a unit length of travel (H/L equals 1). Hereinafter the term *unity gradient* is used to signify this gradient.

Zone 3 (test-pit No. 8) 1.15 feet per minute at *unity gradient.*[6]

Although the clay of Zone 1 lies above the zone of saturation, ground water invariably rises to elevations above its lower margin in borings or test-pits that penetrate the underlying saturated sediments. Thus, in test-pit No. 8 the clays extended down to elevation 305.6 and ground water was not encountered until the underlying sediments of Zone 2 were reached. But when the impervious materials of Zone 1 were pierced, ground water rose to Elevation 307.0. The repetition of this phenomenon was conspicuous during the drilling of the numerous auger borings throughout the area and in borings and test-pits; the clays of Zone 1 form an impervious roof that restrains the ground water from rising to the elevation that conditions of head and hydraulic gradient dictate. When Zone 1 is pierced, water rises to the level of a pressure surface (piezometric surface) indicating a condition of ground water restraint.

Borings that penetrated solution cavities in the bedrock exhibited similar artesian effects and borings drilled from barges in the river frequently experienced artesian flow from bedrock cavities by reason of the low topographic position of the river surface as compared to that of the higher-standing flood plains. The cavities are interconnected laterally but the escape of ground water from them into the overlying sediments is retarded so that openings in the rock behave hydraulically as closed chambers

[6] The first pumping test in this pit was performed when excavation had reached elevation 299.2, and from the data obtained the velocity of percolation of ground water through the sediments of Zone 2 was calculated. The pit was then excavated to near bedrock and another test was performed. Water was pumped from the pit for three days at a rate of 675 gallons per minute and a draw-down was obtained of 21.6 feet. Having noted the cone of ground water depression, the velocities were calculated on the assumption that all of the water was entering through the lowermost 15 feet of the sediments. Although this was the most permeable part, the assumption that it was delivering all of the inflowing water led to a velocity figure that was too high; the actual inflow being through a much larger cross-section than was assumed for purposes of calculation, the velocities of inflow necessary to supply the observed quantities of water were significantly smaller than calculated.

within which circulation is relatively unimpeded but from which escape of water is difficult.[7]

The uplands bordering the valley are overlain with loess and colluvial soil which has been derived from the loess; this mantle is only slightly less impervious than the flood-plain clays and the two materials—one covering the uplands and the other in the valleys—merge at the edges of the valleys to form an almost continuous blanket (Fig. 2). This upland clay mantle is locally imperfect or absent because of recent erosion by small streams, hillside erosion, the presence of rare out-croppings of bedrock and because of road-cuts and other artificial excavations. These local imperfections of the clay cover expose the underlying, more pervious material.

Beneath the loess mantle, the highlands are composed primarily of unconsolidated sediments of Cretaceous age—clayey gravel of the Tuscaloosa formation to the east of the river and sand and clay of the Ripley formation to the west. These Cretaceous sediments possess variable but relatively low permeabilities; the Tuscaloosa gravels are universally very clayey and the Ripley sands are very fine-grained.

The bedrock beneath these Cretaceous formations is irregular, and the few outcrops appear only at the edges of the flood plain. The upper surface of the buried bedrock floor underlying the highlands has in many places been weathered to residual chert and clay that also possess a low permeability.

[7] That cavities beneath the river are sealed in this way has been demonstrated by the behavior of certain borings in the river which, being drilled at the same time, encountered solution cavities and exhibited artesian flow simultaneously. A very slight reinforcement or retardation of the flow from one hole immediately caused a corresponding decrease or increase in the flow from the other hole. The two holes most carefully studied while behaving in this way were located 150 feet apart. Water containing fluorescein dye was pumped into one of the holes at a pressure of 70 pounds per square inch. An artesian flow from the other hole of nine gallons per minute before the test, rose to fifteen gallons per minute within the first minute. The dye appeared in the second hole in five hours. Manifestly, outlets from the bed-rock cavity-system were not sufficiently large or open to permit the dissipation of the pressures thus artificially placed on the boring nor to permit the escape of the dye into the overlying alluvium. On the other hand, the borings possessed free interconnection through lateral passages in the bedrock.

HYDROLOGIC CONDITIONS IN THE HIGHLANDS.

The topographic surfaces within the highlands rise much more rapidly than does the surface of the zone of saturation. Consequently, although the water-table lies well above the adjacent valleys, it does not approach the crests of the highland surfaces. Existing data indicate that the water-table within the highlands probably nowhere stands more than fifty feet above the river except possibly in regions remote from the river where information is not available. A hydraulic gradient, therefore, exists between the highlands and the river, but the effective pressure head is of only moderate magnitude. This low water-table is caused by the loess that overlies the hills, restricting downward percolation and hastening run-off. Rainfall furnishes abundant water but high run-off and low infiltration limit the recharge of the water-table except where imperfections of the loess cover expose the more pervious underlying materials. Moreover, the highlands on both sides of the river are composed of sediments containing clay bodies that intercept water percolating downward, forming perched water-tables and retarding the upward growth of the underlying general zone of saturation.

Highlands West of the River.—The sands of the Ripley formation, which are the principal constituent of the western highlands, are fine-grained and hence only moderately permeable. Rock outcrops, however, are rare to the west of the river and the buried bedrock receives its recharge from these overlying sands, the zone of saturation lying well above the bedrock surface.

Highlands East of the River.—In the immediate vicinity of Kentucky Dam site, the eastern margin of the valley exhibits numerous outcrops and through them surface water finds access to the underlying bedrock cavities through enlarged joints. However, bedrock in no case extends upward to the upper elevations of the topography and recharge through the outcrops is only possible at lower and intermediate elevations. In these highlands, the bedrock is overlain by Tuscaloosa formation and the clayey matrix in which the gravel of the formation is embedded retards downward percolation. Because of this consistently low permeability

of the materials overlying the bedrock, only a very slight differential head exists between these highlands and the river. Most of the recharge of the water-table takes place through the outcrops that occur along the lower and middle slopes. The water-table is mainly confined to the bedrock, only rarely extending upward into the overlying Tuscaloosa formation.

CONTRASTING CONDITIONS ON OPPOSITE SIDES OF RIVER.

It will be noted from the preceding descriptions that the area to the west of the river contrasts with that to the east in that it possesses: (1) a higher water-table, (2) broader flood plain areas, (3) thicker accumulations of river and flood plain sediments, and (4) a broader area of ground water accumulation. For these reasons, the artesian phenomena described in the following topics receive their principal motivation from the west.

In the following topics it is the more pronounced conditions in the area to the west of the river that are principally considered.

HYDROLOGIC CONDITIONS BENEATH THE RIVER AND FLOOD PLAINS.

Flow Through Bedrock and Alluvial Sediments.—The highland areas lying within the Tennessee River drainage, with a width of about eight miles, represent the area of accumulation of ground water. The comparatively limited area of the river bed is the only zone of effluent discharge to the surface. The hydrologic peculiarities beneath the river and flood plains arise from the manner of passage of ground water from these highlands to the river.

As a consequence of the moderate pressure head resulting from the elevation of the water-table in the highlands, a slow migration of ground water toward the river is set in motion and water thus in transit may follow paths through the flood plain sediments or may flow river-ward through the cavity-systems of the underlying bedrock. Equal motivation exists for flow through either of these two routes; the pressure head responsible for the flow is the same in both cases. However, any path laterally toward the river through the flood plain sediments must be by interstitial flow

through restricted pore spaces and retarded by high friction. On the other hand, although the cavity-systems are locally restricted, possess tortuous paths, and probably in most cases are partially filled with insoluble residue, they nevertheless offer slightly less impedance to the flow of ground water. Although these two zones of flow possess different hydrologic characteristics, openings through the bedrock exist which lead to the overlying sediments and transfer of water through these openings from one conduit to the other takes place in a manner and to an extent which is governed by the hydraulic relationships in existence at different localities. Moreover, the sediments, themselves, are not homogeneous; the zone of more permeable sediments that lie immediately above the bedrock surface act in a manner intermediate between the two aquifer-systems; flow through this layer of coarser material is less impeded than through the main body of the sediments, but less free than through the open conduits which penetrate the bedrock.

Paths of Flow Toward the River.—The flow of ground water toward the river is probably along a path that trends (in plan view) diagonally in a downstream direction. The gradient of the river, however, is relatively slight and the fact that little hydraulic advantage arises by reason of discharge farther downstream probably results in ground water flow toward the river by a path that is only slightly diagonal and which approximates the most direct route.

In considering the manner of flow toward the river in vertical section, representative paths may be drawn in the form of the flow-net (Fig. 2). Along each of these paths ground water migrates toward the river. The bedrock being deeply buried by alluvial sediments, all escape of ground water must ultimately be through the sediments that underlie the river, and water thus escaping is subjected to the relatively high friction which these sediments impose, even though the travel river-ward may have been mainly through the relatively open bedrock channels.

Constraint of the Zone of Saturation and Configuration of the Pressure Surface.—The relatively impervious clay of Zone 1 pos-

sesses a variable thickness and in a few places does not extend down quite to the top of the zone of saturation. In such localities, free water-table surfaces exist (Fig. 3). These local areas of free water-table are confined to the " second bottoms " surface to the west of the river; conditions of ground water restraint otherwise are of unbroken continuity from one side of the valley to the other.

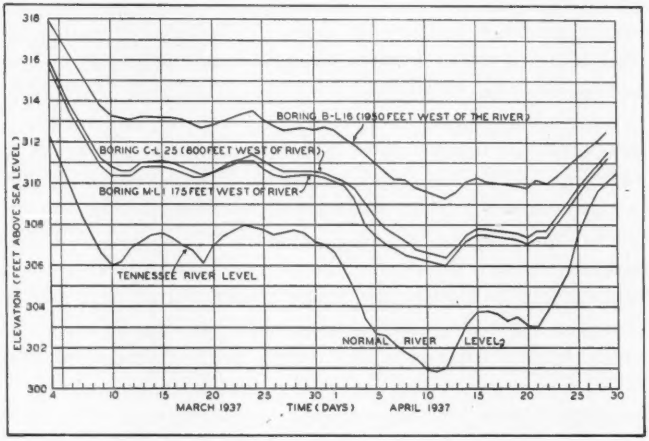

FIG. 4. Fluctuations of river level and sympathetic variations of water levels in borings on the flood plains.

The resulting pressure surface (piezometric surface) originates at the edge of the highlands flanking the valley, descends slowly toward the river, and at the river bank merges with the river surface (Fig. 3). The impervious sediments of Zones 1 and 2 being absent beneath the river, the conditions of constraint are confined to the flanking flood plains and the constrained ground water in the flood plain sediments finds escape into the river channel. Rising slowly from the edge of the river, the pressure surface achieves an average elevation of five feet above the river in the flood plain area until, near the edges of the valley, elevations of from 10 to 20 feet

above the river exist beneath the flood plain and the immediately adjacent highland slopes. This rise continues into the highlands, forming an unconfined water-table at an elevation of about 50 feet above the river (Fig. 2).

The rapid changes in the level of the river cause rapid corresponding changes of the water levels in borings, wells and test-pits (Fig. 4). The calculated velocities of percolation through the sediments are too low to account for these immediate reactions between the river level and the water levels in borings and test-pits by an actual transfer of water by underflow. Rather, the effect is one of pressure; the only actual flow that is necessary for the observed changes of level is that required to fill or empty the borings, wells or test-pits to their new levels, an amount that is quantitatively compatible with the low velocities of percolation.

Additional Pressure Surface Applying to the Bedrock Aquifer-System.—Although the pressure surface indicating the levels to which water will rise in borings and wells penetrating the flood plain sediments of Zone 3 merges with the surface of the river at the river's edge, borings that extend downward into the bedrock underlying the river exhibit artesian flows indicative of a second pressure surface that does not dissipate at the river's edge (Fig. 3). The existence of this second pressure surface arises from the fact (more specifically discussed in a later paragraph) that, while the same initial head motivates flow either through the sediments or through the bedrock, flow through the bedrock cavities encounters less friction and, therefore, suffers less loss of hydraulic head in its passage toward the river.

Velocity of Flow Through the Alluvial Sediments and Through Bedrock.—The permeabilities of the various zones of the alluvial sediments have been measured and the velocities of the flow have been expressed in terms of *unity gradient,* as previously described. Such flow is accompanied by large head-losses due to friction and, under the prevailing conditions of length of travel and hydraulic head, is very slow.[8]

[8] The velocity of flow through the most permeable zone of the alluvial sediments was determined to be (less than) 1.15 feet per minute at *unity gradient.* The ap-

This flow is not uniform through the cross-section of the sand and gravel because of inhomogeneous lithology; more pervious layers doubtless exist but they are laterally discontinuous and surrounded by fine sand that possesses limited permeability. Although flow through the lower-most layers of the alluvial sediments, which are known to be coarse and permeable, is most rapid, ultimate escape of water to the river must be through overlying finer sediments that thus limit and control the velocities of flow through the more permeable materials.

Flow through interconnected passages within the underlying rock approximates "pipe-flow" as contrasted to the interstitial flow through the alluvial sediments; interconnected conduits exist in the limestone which, although possessing variable diameters, are open. However high the friction associated with bedrock flow may be because of the irregularities of these conduits, it is none the less smaller than through the flood plain sediments.

Escape of ground water from bedrock to the river is only possible by passage through the intervening sands and gravels and the velocity and quantity of flow through the cavity-systems in bedrock are therefore determined not by the size and freedom of the conduits, themselves, but by external conditions that limit their discharge. The overlying alluvial sediments possess relatively low permeabilities and water escaping upward through them must necessarily flow in a direction roughly normal to their bedding—the direction of lowest permeability.

Subsequent consideration will more specifically define the relative velocities through bedrock conduits and through the overlying sediments; for the present it suffices to note that the actual

proximate order of magnitude of the velocity of flow under field conditions may be obtained by substituting appropriate values in the following equation stating Darcy's Law: V equals K H/L, where V equals velocity, H equals total head, and K is the velocity of percolation at *unity gradient*.

Assuming that at a point in the highlands 10,000 feet west of the river, the water-table stands at elevation 350 feet and that the ground water flow is toward the river whose surface is at elevation 302 feet, the following substitutions can be made:

H equals 48; L equals 10,000; K equals 1.15; V equals K H/L = 1.15 48/10,000 = 0.0054 feet per minute (velocity through the pores of the alluvial sediments).

velocity of flow through the cavity-systems is less than the potential capacity of these conduits.

Potential Energy in the Bedrock Aquifers.—Escape from the bedrock cavities being restricted by the overlying alluvial sediments, the comparatively open bedrock aquifers pass water only to a degree that is less in quantity and velocity than their potential capacity. The difference between the reduced amount of water which, by reason of external constraint, is flowing through the bedrock conduits and the total amount that a conduit of this type and size would transmit if unobstructed egress was permitted (under the existing conditions of head, length of travel and friction) represents a reserve of potential energy. It is this potential energy, in the form of hydraulic head, which permits bedrock water to rise in borings penetrating cavities to elevations above the free surface of the river, or, on the land, above the pressure surface which applies to the overlying alluvial sediments.

Components of the Hydraulic Head.—Total hydraulic head that controls flow of water may be considered as the algebraic sum of the pressure head, velocity head, and friction head. These constituents of the total head may be casually defined as, respectively, the head resulting from advantage of position (possessing potential energy as a result of elevation), the head associated with flow (possessing kinetic energy as a result of momentum), and the head (a negative quantity) lost by friction. Initially, ground water within the area under discussion possesses pressure head as a consequence of the elevated position of the water table in the highlands, velocity head because of the slow river-ward flow, and friction head because the aquifers present frictional resistance to flow.

Artesian effects do not occur in borings penetrating the alluvial sediments underlying the river, the conditions of restraint existing beneath the flood plains having ceased at the river's edge and the river consequently possessing a free surface; the original head resulting from the elevation of the water-table in the highlands has been dissipated in friction. It may be said that velocity head and pressure head in the alluvium have decreased to zero at the river

surface and that the friction head has grown to equal the original total head (Fig. 3).

Ground water in bedrock conduits beneath the river rises through borings as artesian flows. If the fountain-head of these flows is four feet above the river surface, it may be said that the friction head for bedrock ground water (at this point) is four feet less than the friction head for ground water in the overlying alluvial sediments (or four feet less than the original total head). The four feet of residual head in the bedrock aquifers is composed of velocity head and pressure head (Fig. 3), the pressure head being much the larger component because of the slow velocity of bedrock flow.[9]

It is worth noting that rapid velocities of flow are required to develop significant velocity heads, as can be demonstrated by resort to the following formula: V^2 equals 2 GH, where V equals velocity, G equals the acceleration due to gravity (32.16 feet per second) and H equals head.

Assuming a four-foot velocity head the following substitutions can be made: V^2 equals 2 GH $= 2 \times 32.16 \times 4$, equals 257.28. V equals $\sqrt{257.28} = 16.04$ feet per second (velocity of flow required to develop a four-foot velocity head).

Substitution of smaller heads in the above equation establishes the fact that any flow of the slow velocities that might reasonably be expected to occur in the bedrock would result in negligible velocity heads.

If the assumption of velocity head of sufficient magnitude to develop the observed four feet of differential head is untenable, it can further be pointed out that the initial pressure head, originat-

[9] It has previously been noted that this difference of head in the bedrock and in the alluvium resulted from a reserve of potential energy in the water in the bedrock caused by the restriction of the flow through the cavities to quantities below their transmission-capacities. The fact that this energy is potential energy indicated that the excess head resulted from the accumulation of either an increased pressure head or a deficiency of friction head in the bedrock aquifers. That is, if the observed four feet of differential head had resulted from an excess of velocity head it would have had to develop from rapid flow through the bedrock and the implied energy would have been kinetic rather than potential. The assumption of high velocity and consequent excess of kinetic energy in the bedrock is contrary to previous considerations concerning the conditions governing flow through the bedrock.

ing in the highlands, is equal for both the ground water in the alluvium and that in the bedrock. By elimination, the observed four feet of differential head observed in the river must therefore be the result of different friction heads within the bedrock and the alluvial sediments.

Relation of Length of Travel to Position of the Pressure Surface.—At the river's edge the pressure surface applying to the water within the bedrock lies four feet above the pressure surface applying to the ground water within the overlying alluvial sediments. In the highlands the water-table represents a single free surface. At some intermediate point, ground water divides and begins its flow to the river as two increments, one in the bedrock and one through the overlying alluvium. Immediately upon the inception of this divided flow, friction develops that is different for the two increments; high through the sediments and relatively low through the bedrock. At the same time a pressure surface that applies to the bedrock ground water diverges from the water-table surface, lying above it. As the flow through the alluvial sediments passes beneath the constraining blanket of clay on the flood plains, the free water-table of the highlands merges with a pressure surface applying to the water within the sediments. These two pressure surfaces persist across the flood plain, the one applying to the ground water within the bedrock diverging by larger and larger amounts as the river is approached until, at the river's edge, where the lower surface merges with the river, a four-foot differential in height has accumulated.

The cumulative divergence between the two surfaces (which start in the highlands as a single plane) results from the progressively developing friction head in the two aquifers; the friction head developing in the alluvial sediments accumulates with greater rapidity as the river is approached than does the friction head in the bedrock.[10]

[10] Schematically, this relationship can be illustrated by an hypothetical example: consider the losses of head in two aquifers to be: for aquifer A, 1 foot of head-loss per 10 feet of travel, and for aquifer B, two feet of head-loss per 10 feet of travel. If pressure surfaces for both aquifers start as coincident planes, the divergence will be one foot after 10 feet of travel, 2 feet after 20 feet of travel, 3 feet after 30 feet of travel, and so on.

While both surfaces are depressed to lower elevations as the river is approached, as a consequence of the growth of the respective friction heads, the amount of divergence stands in direct ratio to the length of this divided flow, and also proportional to the angle of divergence. At Kentucky Dam site, with a distance of travel of only a few miles (distance to ground water divide), and only a slight angle of divergence of the two surfaces (friction in the two aquifers is of the same order of magnitude), a divergence of only four feet results.[11]

Interchange of Water Between Bedrock and the Superjacent Alluvium.—The pressure surface applying to the alluvial sediments results from the presence of the impervious clays of Zone 1, as previously described. The distinct and higher pressure surface applying to the bedrock aquifers is similarly the result of confinement, upward escape from the bedrock conduits being hindered by the limited permeability of the overlying sand and gravel (sediments of Zone 3) and by the debris in the outlet-channels.

The seal thus developed is imperfect and water doubtless passes, although with difficulty, upwards from the rock. The develop-

[11] Mr. E. A. Prokop states (personal communication) that during exploration for structures on the Detroit River for the Detroit Water Works, an artesian pressure of ten-feet was encountered. He believes that this phenomenon is explicable in the same terms as the artesian pressures at Kentucky Dam site and describes conditions involving greater length of travel, which he feels are responsible for the larger artesian head. In other cases, greater differences between the friction of flow through the bedrock and through the superjacent sediments would accomplish the same result; with small angles of divergence between the two pressure surfaces (small friction differences in the two aquifers) and long paths of travel, large total divergences would result, but the equal divergences would be possible with shorter paths of travel but with larger angles of divergence (large friction differences in the two aquifers). The total head does not affect the amount of divergence of the two surfaces except that the divergence in no case can exceed the total head.

In the vicinity of the Detroit Water Works the ground water is impregnated with hydrogen sulphide. Special design was necessary to prevent seepage of water containing this noxious gas, impelled by artesian pressures, from entering subsurface tunnels. In connection with gravity dams, similar artesian pressures would be significant because the base of the structure would be acted upon by this force applied vertically upward, opposite to the force of gravity which prevents overturning and sliding. If neglected, the effect would be an encroachment on the factor of safety.

ment of the observed differential heads within the two aquifer-systems would not be possible, however, if escape of ground water from the bedrock was extremely easy; as previously explained, the development within the bedrock cavities of potential energy which is available for translation into head arises from the existence of a greater capacity of the bedrock aquifers for lateral flow than for vertical escape.

Theoretically, this condition would be fulfilled by either (1) rapid leakage from the bedrock into the overlying sediments, accompanied by rapid lateral flow from the highlands or (2) slow leakage accompanied by slow lateral flow (equal friction heads could be developed in both cases). Exploratory borings indicated that escape of water to the bedrock surface is not great in amount, a condition which implies slow flow through the bedrock aquifers.[12]

The bedrock and the alluvium, therefore, act as separate conduits, possessing distinct hydrologic properties. Leakage from the bedrock conduits upward into the alluvial sediments is very limited in amount. From this conception, it must be concluded that recharge of both aquifers is mainly by independent lateral flow from the highlands. Insofar as slow flow takes place through bedrock, equivalent upward escape from the bedrock must occur and to this limited extent contribute to the recharge of the superjacent alluvium; this flow, however, is not the main increment of recharge for the alluvial aquifer.

CONCLUSIONS.

The conditions necessary for the development of the artesian effects described are, in their simplest form: a clay mantle over the flood plain surface, extending down to elevations below the

[12] Generalizations concerning the effective size of bedrock conduits can be derived from these considerations. The necessary calculations require that various assumptions be made and mathematically tested and are too voluminous for detailed presentation. They lead to the conclusion that the bedrock conduits possess small effective diameters.

The same mathematical manipulations indicate that any large quantity of ground water flow through bedrock could not be maintained for more than a few days or weeks before depletion of the ground water storage in the highland areas of accumulation.

normal water-table; a zone of permeable sediments beneath the clay; and highlands flanking the valley of sufficient magnitude to permit the development of a ground water gradient of significant inclination and consequent hydraulic head. In the region herein discussed, the presence of solution cavities in the limestone bedrock permits a dual artesian effect. The artesian conditions exhibited by the bedrock aquifers are entirely independent of the flood plain clays, resulting solely from the relative restraint imposed by the overlying sands and gravel. Inasmuch as these geologic conditions are found generally along the lower Tennessee, Cumberland, and Ohio rivers, it is probable that the hydrologic conditions are similar throughout these areas.

In many terrains not underlain by soluble bedrock, open joints or fracture planes doubtless allow bedrock flow similar to that described through the limestone at Kentucky Dame site.

Innumerable large rivers flow in valleys which satisfy these requirements and the phenomena described probably occur more commonly than has been realized.

ACKNOWLEDGMENTS.

The writer is indebted to his engineering and geological associates in the Tennessee Valley Authority, especially to the staff of the Kentucky Project. Particular mention must be made of the cooperation of Major E. C. Eckel, Chief Geologist, Mr. Berlen C. Moneymaker, Assistant Chief Geologist, and A. J. Mistler, Junior Geologist at Kentucky Dam. Mr. James B. Hays, Construction Engineer, has contributed discussion and advice of the most helpful kind. Special acknowledgment must be made of the assistance of Mr. E. A. Prokop, Reservoir Construction Engineer, in charge of the preliminary investigations of the Kentucky Project, who has maintained a constant interest in the development of the hydraulic data, artesian and otherwise, at Kentucky Dam, and who has critically analyzed this theory of artesian flow. Professor Allyn C. Swinnerton has contributed assistance in critically reading the manuscript.

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PIPE DEPOSITS OF THE COPPER CREEK AREA, ARIZONA.

TRUMAN H. KUHN.

ABSTRACT.

The Copper Creek area is in eastern Pinal County, Arizona. Cretaceous (?) sediments, interbedded with a complex series of andesitic volcanic rocks are intruded by granodiorite and overlain by basaltic lava flows.

Faulting is prominent and of two ages. The first preceded, and in part, controlled the granodiorite intrusion, and the second followed its consolidation. The many breccia pipes that stud the area are in strong fault zones or at intersections of faults. The pipes are believed to be the result of solutions acting on fractured areas. The advanced stage is complete silicification of parts of the breccia.

Between 1863 and 1939, metals, of which molybdenite is the most important, valued at approximately $3,500,000 have been recovered. The Childs-Aldwinkle mine, the largest producer, is a pipe deposit with the molybdenum and copper sulphides in the spaces between granodiorite breccia fragments, and generally replacing earlier gangue minerals. Molybdenite, in the Childs-Aldwinkle mine is the latest hypogene sulphide. The deposit is considered to be in the mesothermal temperature range. Other pipes have yielded copper ore.

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INTRODUCTION.

THE Copper Creek area is 60 miles northeast of Tucson, Arizona, in the Galiuro Mountains, and is reached by a road that leaves the Tucson-Winkelman highway at Mammoth.

Little has been published on the geology of the Copper Creek area. Weed, consultant for one of the early mining companies, was interested in the origin of the numerous pipes of the area.[1] Darton shows a generalized east-west section along Copper Creek.[2] The general physiography of the northwestern portion of the Galiuro Mountains is discussed by Davis.[3] In addition to the published information, several private reports on the various mines of the area have been available.

The writer is indebted to W. C. Rigg, President of the Arizona Molybdenum Corporation, Frank Fields, Manager of the Blue Bird Mining Company, Martin E. Tew, President of the Copper State Mining Company, and H. M. Lavender, General Manager of the Phelps Dodge Corporation. Without the cooperation of these men in granting free access to the various mining properties and making available maps and records of their companies, much of this work would not have been possible.

[1] Weed, W. H.: "Chimney" or "pipe" deposits in the porphyries. Min. Eng. World, 38: 376, 1913.

[2] Darton, N. H.: A resumé of Arizona geology. Ariz. Bur. Mines Bull. 119: 272–74, 1925.

[3] Davis, W. M., and Brooks, Baylor: The Galiuro Mountains, Arizona. Am. Jour. Sci., 5th series, 19: 100, 1930.

B. H. Martin and R. S. Camp of the Arizona Molybdenum Corporation provided maps and information concerning the inaccessible portions of the Childs-Aldwinkle mine.

Drs. B. S. Butler, M. N. Short, and R. M. Hernon of the University of Arizona offered invaluable suggestions and criticisms.

ROCKS OF THE AREA.

Cretaceous (?) sedimentary rocks are interbedded with a complex series of andesitic tuffs, flows, and intrusives. These are overlain by an extensive series of flat-lying basaltic flows. A medium-grained rock of variable composition, but predominantly granodiorite, intrudes the sediments and andesite tuff.

Earlier Sediments and Volcanic Rocks.—The earlier sediments of the Copper Creek region are confined to a narrow band lying between the granodiorite and the basalt flows. They consist of quartzite, limestone, shale, conglomerate, and sandstone, and are probably Cretaceous.

The andesite tuff is a complex series of andesite, rhyolite, and dacite tuffs and flows intruded by sills and dikes of andesite and dacite.

A series of basalt flows covers the larger part of the Galiuro Mountains, but the flows are exposed in the Copper Creek area only along the eastern and northern borders. These rest unconformably upon the Cretaceous (?) rocks.

Intrusive Rocks.—Granodiorite has intruded the Cretaceous (?) rocks as shown by dikes and plugs in the andesite tuff. The relation between the granodiorite and basalt flows could not be determined. The gray, brown, and buff granitoid rock is predominantly granodiorite but ranges in composition from a quartz monzonite and monzonite to quartz diorite and diorite. There is a variation in texture from fine-grained equigranular to medium-grained porphyritic rocks. Short latite and andesite dikes intrude both the granodiorite and andesite tuff.

Gila Conglomerate.—The upper Pliocene [4] Gila conglomerate

[4] Knechtel, M. M.: Geologic relation of the Gila conglomerate in southeastern Arizona. Amer. Jour. Sci., 31: 86, 1936.

consists of a thick deposit of fairly well consolidated clay, sand, and gravel that has been faulted against the andesite tuff.

STRUCTURE.

Faulting is the most prevalent structural feature and the several systems of fractures are present in all kinds and ages of rocks in the district. However, all of the faults were not formed at the same time. The granodiorite intrudes the earlier andesite tuff and has entered the andesite, in places, along east-west and N. 70° W. breaks that were formed before or at the time of intrusion of the granodiorite. The same system of forces seems to have formed faults with the same attitude in the granodiorite after it consolidated.

Breccia pipes are closely associated with faults. Movement along fault planes is not considered the only factor in brecciation, but it is believed that strong faults and intersection of faults have controlled the passage of solutions that produced brecciation.

Movement along a fault fronting the Galiuro Mountains on the southwest has tilted the lava flows to the northeast.

Sequence of Structural Events.—Folding of the Cretaceous (?) tuffs, flows, and sediments, probably near the beginning of the Laramide Revolution, is the earliest record of deformation in the Copper Creek area. Extrusion of basaltic flows followed erosion of the Cretaceous (?) rocks. Rotational forces acting in a northwest-southeast direction caused faulting in the andesite tuff, which, in part, controlled the intrusion of the granodiorite. Although evidence of intrusion of the andesite tuff by granodiorite is established, the relation between the granodiorite and basalt flows is not known. Renewal of the stresses affected the entire region, after solidification of the granodiorite. The rotational stresses were followed by the formation of the breccia pipes, and these in turn by deposition of ore minerals, and post-ore movement along some faults. The latest structural event was the tilting of the entire block along a fault that cuts the Gila conglomerate.

Faulting.—Few large faults are present in the Copper Creek area. Four general directions of faulting, east-west, N. 60° E., N. 70° W., and N. 10° W. have been determined. In addition, one fault with considerable breccia strikes N. 55°–60° W., and the fault contact between the andesite tuff and Gila conglomerate strikes northwest. Close determination of the direction and amount of movement by faulting within the area cannot be made due to the absence of persistent mappable units.

The breccia pipes are associated with one or more of the principal systems of faults. Most of the individual faults can be traced only a few hundred or a few thousand feet, but some have been followed vertically for 850 feet and traced on the surface for a mile. They are nearly vertical. The outcrops are straight, highly silicified bands, one-half to 4 inches wide, stained reddish-brown by iron oxide. A little copper and lead has been noted in them. Underground at the Childs-Aldwinkle mine, faults of the east-west system contain 1 to 3 feet of gouge, which suggests that this is a direction of shearing. The N. 60° E. system of faults is considered to be a direction of tension.

East-west faults predominate and are associated with most of the pipes. N. 60° E. faults are important both in their association with pipes and because the vein deposits of the region, notably the Blue Bird, strike in this direction. Throughout the Copper Creek region are tight faults striking N. 10° W. They are not numerous, but are present near most of the breccia pipes and in the Childs-Aldwinkle mine appear to control the locations of the ore bodies.

The contact between the Gila conglomerate and andesite tuff is a fault that strikes N. 25° W. and dips about 50° SW. The amount of movement could not be determined in the limited area studied. Davis [5] considered that this fault divided the original northern Galiuro Mountains into two parts, one of which was uplifted into the present position of the range block and the other was relatively depressed along the site of the San Pedro trough.

[5] Davis, W. M.: *op. cit.*, p. 98.

Age Relations.—Faults of the four major directions cut all rocks except the Gila conglomerate and probably originated before or during the granodiorite intrusion and continued after it. Post mineral movement is indicated by slight displacement of ore-bearing faults. Faults of each system displace faults of all systems. The fault separating the Gila conglomerate and andesite tuff intersects all structures in the igneous rock.

Jointing.—Jointing is intense in the granodiorite and andesite tuff. Joint planes strike parallel to the four major fault directions, east-west, N. 60° E., N. 70° W., and N. 10° W. In the granodiorite, jointing breaks the rock into 3 to 5 foot blocks, but near the Childs-Aldwinkle mine the jointing is closer and the blocks smaller.

Structural Features of the Cretaceous (?) Sediments.—The same forces that caused fracturing and faulting in the granodiorite and andesite tuff affected the Cretaceous (?) sediments. Fractures striking east-west and N. 60° E. are common in the limestone, but generally re-cementation has obscured the fracturing. The sediments were folded into sharp anticlines and synclines before faulting.

Structural Features of the Pipes.

The 100 to 125 pipes of the Copper Creek area early attracted prospectors. Most of them have been prospected, but only a few have been productive.

The term "pipe" as used in this paper refers to breccia bodies rudely circular or elliptical in plan and having a great vertical extent. "Chimney" is used synonymously with "pipe." W. H. Emmons[6] has used the term "diatreme" for pipes formed by explosive action. A pipe is generally considered to be ore bearing; however, similar structures occur that do not contain ore minerals.

Childs-Aldwinkle Pipe.—The Childs-Aldwinkle pipe, which contains the most important ore deposit in the district, is approxi-

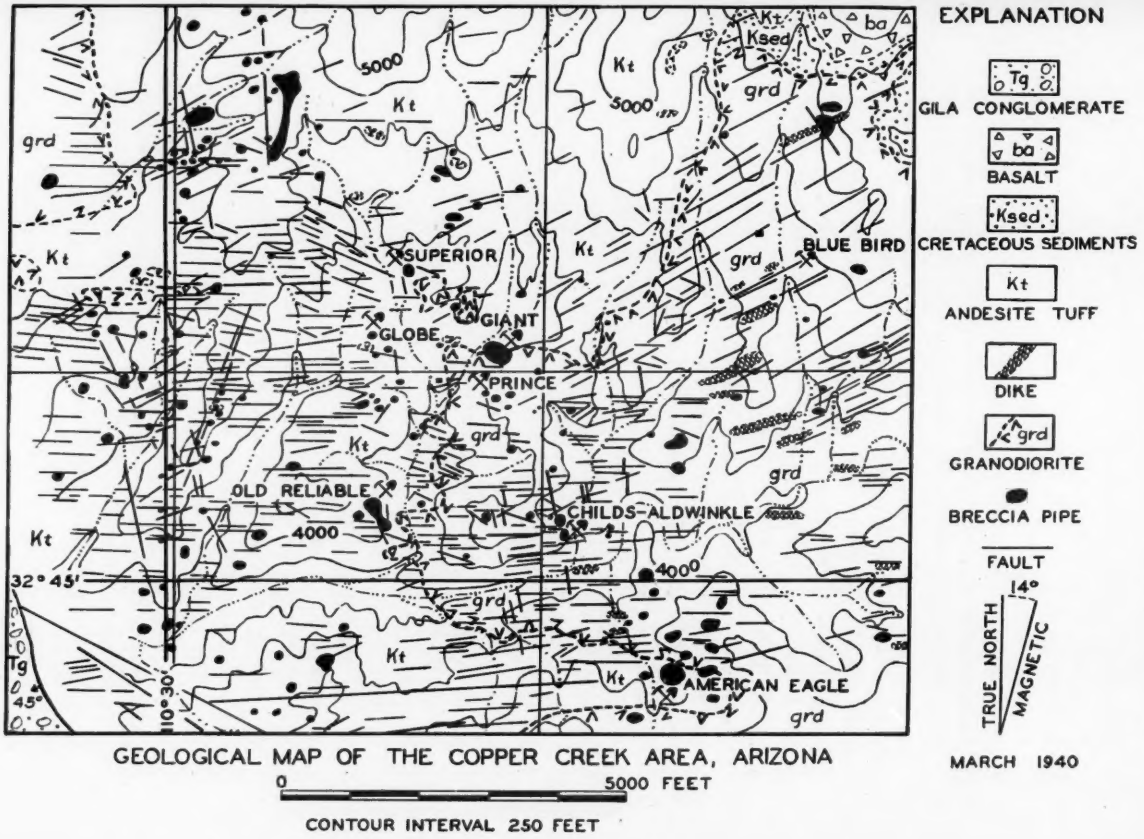
[6] Emmons, W. H.: Diatremes and certain ore bearing pipes. Min. Tech., May, 1938.

mately one-fourth mile west of Copper Creek post-office. Before the caving of the glory holes, two oval-shaped breccia outcrops separated by fairly fresh, unbrecciated granodiorite were aligned in a N. 10° W. direction (Fig. 1). The northern breccia body, with maximum and minimum dimensions at the surface of 270 feet by 150 feet, is nearly vertical. The breccia mass gradually changes in size and shape until, 450 feet below the surface, it is almost circular with a diameter of about 115 feet. The southern branch, with an outcrop 220 feet by 100 feet, dips 75° N. and

FIG. 1. Looking west at glory holes of Childs-Aldwinkle mine.

joins the northern body at a depth of 450 feet. At 510 feet, the pipe has a dimension of 210 feet by 170 feet, and gradually diminishes to 160 feet by 140 feet on the bottom level of the mine, at a depth of 820 feet. Exploration by winzes and diamond drilling strongly suggests that the area of brecciation has diminished greatly at 900 feet below the surface.

The Childs-Aldwinkle pipe is in a zone of strong east-west fractures and faults. Two of the stronger of the east-west breaks have been traced, with a fair degree of certainty, through the mine. A N. 10° W. fault is present on most levels and a similar



GEOLOGICAL MAP OF THE COPPER CREEK AREA, ARIZONA

FIG. 2.

fault shows on the surface between the glory holes. Three N. 10° W. faults at the bottom of the mine suggest a fracture zone. The N. 60° E. and N. 70° W. systems, so strongly represented on the surface, were also observed underground, and faults with attitudes other than the four major systems are present. The striae on most slickenside faces are horizontal. Minor displacements have occurred after the formation of the breccia. In a few places, small discontinuous fault planes form the contact between breccia and granodiorite. On the 820-foot level, a small area of breccia with gangue and sulphide minerals has been slightly crushed. All major faults contain sulphides, indicating pre-mineral origin. Small post-mineral movement has displaced N. 10° W. faults.

The pipe of breccia consists of angular blocks of altered granodiorite cemented by gangue and ore minerals. In places, semi-rounded fragments of granodiorite show alteration envelopes paralleling the surface of the block. Dimensions of the blocks range from one inch to 15 feet and average 6 to 12 inches. The contact between the brecciated and non-brecciated material is, in general, sharp.

In the central portion of the breccia mass, on the 820-foot level, the granodiorite blocks are entirely replaced by sericite, quartz, and sulphides. The zone surrounding the central zone is composed chiefly of chlorite, quartz, and orthoclase with minor apatite and sulphides. The granodiorite has been entirely replaced, but the outline of the blocks can be seen. On the 780-foot level, the sericitized zone grades into the chlorite zone, but here the texture is coarse and pegmatitic. Orthoclase occurs in anhedral crystals up to 6 inches long. The chlorite crystals are up to 2 inches across. This pegmatitic mass is closely associated with a N. 10° W. fault. Surrounding the zone of intense chloritization is the typical breccia of the pipe. On the 820-foot level, the breccia is composed of 9- to 15-inch angular blocks of altered granodiorite, surrounded and cemented by coarse-grained chlorite, quartz, and orthoclase. The cementing material comprises up to 50 per cent of the mass. Toward the solid wall the blocks increase in size and there is a very noticeable decrease in the amount of cementing

material. In places, the chlorite and quartz matrix is less than 10 per cent of the total breccia.

The blocks of granodiorite diminish in size from an average of 10 to 12 inches in diameter on the lower levels to 3 to 6 inches in the upper levels. However, everywhere the brecciated fragments vary in size; some 15-foot blocks are surrounded by fragments only a few inches across. The cementing material also changes from principally chlorite and quartz at the bottom of the mine to sericite and quartz in the upper levels. At the borders the breccia usually grades into soft, much altered granodiorite, and this in turn into hard jointed granodiorite. The jointing breaks the rock into fragments similar in sizes and shapes to those in the breccia, but showing no dislocation. Small offshoots 10 to 20 feet in diameter that branch from the main pipe show the same type of brecciation as the main pipe.

Open vugs occur throughout the mine but are more numerous on the upper than on the lower levels.

Other Pipes of the District.—Of the other 100-odd breccia pipes of the Copper Creek area, only one could be examined below the surface. A tunnel, 225 feet below the elongated outcrop of the Old Reliable pipe, reveals a brecciated mass 600 feet by 100 feet. The breccia is composed of altered, angular and sub-angular fragments of andesite tuff 2 inches to 36 inches in diameter that persists to a depth of at least 450 feet below the surface. The cementing materials, quartz, sericite, and sulphides, in places entirely fill the space between the blocks, but in other places, the matrix does not fill the interstices and leaves an open mass of well-rounded, strongly silicified fragments. The central portion of the pipe is highly silicified. The contact zone between the breccia and non-brecciated andesite tuff is gradational, but narrow. Most of the faults in the Old Reliable pipe strike east-west, with the N. 60° E. system much less developed. A few N. 20° W. and N. 10° W. faults were recognized.

A group of pipes, which include the Copper Prince, Globe, and Superior, about two-thirds of a mile northwest of the Childs-Aldwinkle mine, was prospected in 1907–09 by the Calumet and

Arizona Mining Company. The upper levels of the Copper Prince were mined by the Arizona Molybdenum Corporation in 1937.

The breccia at the Copper Prince consists of angular and subangular blocks of granodiorite, ranging from 3 to 9 inches in diameter, surrounded and cemented by silica, sericite and sulphides. The breccia outcrop, an elliptical, iron-stained mass rising 25 feet above the granodiorite, shows little of the true character of the brecciation. At a depth of 420 feet, the pipe has tapered to a vein.[7] In the vicinity of the pipe are several faults striking east-west, N. 70° W., and N. 10° W.

The Globe workings prospect a compact group of three breccia pipes cropping out 1,500 feet west of the Copper Prince. The outcrops are made up of angular to well-rounded fragments of andesite, 1 to 3 inches in diameter, cemented by quartz. Most andesite blocks are altered to quartz and sericite. Large massive blocks of andesite tuff occur with the breccia. The contact between the breccia and non-brecciated rock is sharp and nearly vertical. Faults striking east-west, N. 60° E., and N. 10° W. are associated with the Globe group. The pipe has been explored to a depth of 600 feet.

The Superior pipe, 1,000 feet north of the Globe, is one of the most conspicuous breccia outcrops of the Copper Creek district (Fig. 3). It is composed of an open mass of angular and rounded andesite tuff fragments, ranging from 8 to 12 inches in diameter. Large, massive blocks of andesite form part of the outcrop. Numerous faults surround and pass through the outcrop.

The American Eagle pipe, one-half mile southeast of the Childs-Aldwinkle mine, although broken and altered, shows less brecciation than the pipes already described. The outcrop is fractured, but the replacing materials, quartz, sericite, tourmaline, and sulphides, only occupy fractures cutting the andesite. The Amer-

[7] Locke, A.: The formation of certain ore bodies by mineralization stoping. ECON. GEOL., 21: 441, 1926.

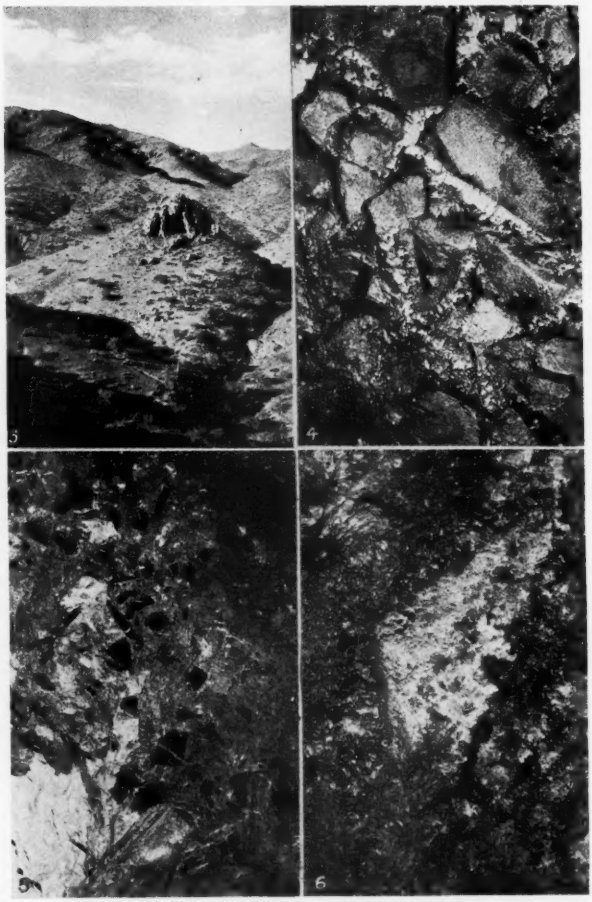


FIG. 3. Outcrop of Superior pipe.

FIG. 4. Breccia from outer zone on 820-foot level of Childs-Aldwinkle pipe.

FIG. 5. Angular breccia in Childs-Aldwinkle pipe, 800 feet below the surface.

FIG. 6. Granodiorite on 820-foot level of Childs-Aldwinkle pipe replaced by sericite, chlorite, and quartz.

ican Eagle pipe is in a strong zone of faults striking east-west and cut by cross-faults striking N. 60° E. and N. 20° E.

Scattered over the Copper Creek area are numerous other pipes (Fig. 2). They differ widely in size, appearance, outcrop, and brecciation.

Near the northwest corner of the region shown on Fig. 2 is a large group of pipes that exhibit better than any other group in the area a relation to faults. The pipes are aligned along faults striking east-west and N. 60° E. and seem to be localized by less strong cross faults. At places, the faults striking east-west and N. 60° E. widen to form short lenticular outcrops similar in appearance to the pipe outcrops. The character of brecciation of these pipes differs somewhat from that of pipes in the central part of the area examined. An open aggregate of more or less parallel, rectangular plates of andesite tuff averaging one-half inch by 4 inches by 6 inches, and cemented by silica make up the breccia.

The outcrops of a pipe 1,000 feet west of the Childs-Aldwinkle mine contain numerous open spaces filled with large well-formed quartz crystals, and in a tunnel 300 feet below this outcrop, sericite has almost entirely replaced quartz as the alteration mineral and the pipe is only slightly brecciated. Associated with the brecciation in the pipe, at the lower level, is a conspicuous mass of latite which was not found on the surface, suggesting a relation between intrusion of dike rock and the formation of breccia pipes.

Scattered throughout the Copper Creek area are small plugs of silicified and sericitized rock which do not show the brecciation so common to most of the pipes. In the same category are numerous outcrops of almost pure quartz which represent advanced stages of replacement.

With few exceptions, the pipes of the Copper Creek district have the same general appearance; iron oxide staining a resistant, silicified, circular or elliptical mass, standing 5 to 50 feet above the surrounding rock. The breccia is, in general, composed of angular to rounded fragments of the host rock varying in size from 1 inch to 50 feet. The cementing materials are quartz, sericite, chlorite, tourmaline, and sulphides, and comprise 5 to 50

per cent of the total mass. The outcrops of a few pipes are made up entirely of silica. All pipes are in strong fault zones usually associated with one or more cross fractures.

Origin of the Pipes of the Copper Creek Area.

The literature on pipes gives at least four different explanations of their origin.

The Jessie pipe near Breckenridge, Colorado, is an oval area, 900 feet by 600 feet, of monzonite porphyry fissured in many directions. Ransome[8] considered this pipe formed ". . . by stresses that were relieved merely by the opening of many small cracks in the porphyry and that they were not productive of much displacement."

Explosions caused by invading solutions is considered by Emmons[9] as an important cause of pipes. A tendency in recent years is to regard many pipes as channels formed through the agency of volcanic gases under high pressure. This explanation, however, has long been advanced for many pipes throughout the world.

Locke[10] has offered a third explanation for the origin of pipes. He suggests that they may be formed by the solution of rock along trunk channels by rising solutions during an early stage of their activity. This would be followed by a collapse and brecciation of the rock thus left unsupported, affording easy access by mineralizing solutions. Locke bases his conclusions on observations made in the Pilares mine, Sonora, Mexico.

Replacement by ascending solutions is a fourth possible method of forming breccia pipes. The O.K. chimney in the Beaver Lake district, Utah, described by Butler[11] is

[8] Ransome, F. L.: Geology and ore deposits of the Breckenridge district, Colorado. U. S. Geol. Surv. Prof. Pap. 75: 144–147, 1911.

[9] Emmons, W. H.: Diatremes and certain ore bearing pipes. Min. Tech., May, 1938.

[10] Locke, Augustus: The formation of certain ore bodies by mineralization stoping. ECON. GEOL., 21: 431–453, 1926.

[11] Butler, B. S.: Geology and ore deposits of the San Francisco region, Utah. U. S. Geol. Surv., Prof. Pap. 80: 172–178, 1913.

> . . . associated with fractures along which there has been a brecciation of the rocks but not extensive displacement.

The chimney consists of pegmatitic quartz surrounded by altered and mineralized quartz monzonite. The ore and gangue minerals were deposited in spaces between corroded fragments of quartz monzonite. Butler suggests, however, that the spaces occupied by the ore and gangue minerals were formed largely by the solution of the rocks in the early stages of mineralization and not by dynamic movement. The solutions were relatively confined and the dissolving activity was strong, resulting in the formation of a cylindrical channel with a maximum dimension of 100 feet.

The pipes at Copper Creek more closely resemble the solution chimney described by Butler.[12] At Copper Creek, the pipes are in strong fracture zones or at intersections of fractures. Solutions that rose along these fractures altered and dissolved the rocks and thus produced breccia. Further brecciation may have resulted from slumping, similar to that described by Locke[13] in the Pilares mine. All gradations exist between pipes intensely altered and brecciated to those that show a strong fracture pattern with very little alteration.

Discussion of Origin.—Arguments against brecciation by ascending solutions:

1. On the 400-foot level of the Childs-Aldwinkle mine are typical fault breccia fragments of quartz.

2. The granodiorite fragments of breccia in the Childs-Aldwinkle and Copper Prince pipes and the andesite fragments in the other pipes are too angular to be caused by any method other than mechanical.

3. A number of pipes are at intersections of 2 or more faults and brecciation might be expected at these crossings.

4. Large volumes of solutions have passed through the pipes and may have removed considerable material permitting slumping.

[12] Butler: *op. cit.*

[13] Locke, A.: *op. cit.*

Arguments for brecciation by ascending solutions:

1. Underground, as the Childs-Aldwinkle pipe is approached, there is a gradual change from unaltered to altered granodiorite; from granodiorite blocks slightly separated by gangue minerals (Fig. 4), to blocks widely separated (Fig. 5), and finally to complete change of the granodiorite by the altering solutions (Fig. 6). In the Old Reliable mine, the same conditions exist except that andesite and not granodiorite has been altered.

2. In many places, non-rotated blocks are separated along joint planes by only small bands of gangue.

3. The character of the rock outside the pipe shows that jointing is sufficiently intense to permit the passage of altering solutions and is of a pattern and size to produce the blocks in the pipes.

4. The contact between the brecciated and non-brecciated rock, while sharp, is gradational and too irregular to be explained by movement.

5. Alteration rims are found around both angular and rounded breccia blocks.

6. Some areas, in which angular blocks suggest rotation, grade directly to regions of non-rotated fragments.

Conclusions.—

1. The intersection of the east-west, N. 60° E., N. 10° W., and N. 70° W. systems of faults, fractures, and joints has broken, without marked rotation, masses of rock into small blocks sufficiently permeable to permit passage of altering solutions.

2. Altering solutions were localized in a small area within the broken zone by fissures, which in the case of the Childs-Aldwinkle mine probably strike N. 10° W.

3. Altering solutions ascending fractures and joints were guided and controlled by large faults. These solutions caused replacement of the rock adjacent to the joints and fractures by chlorite, sericite, quartz, feldspar, and tourmaline, which gradually destroyed the rock, until, in places, it was entirely replaced by secondary minerals.

4. In some pipes, as the Childs-Aldwinkle, Copper Prince, and those in the western portion of the area, the altering process formed, principally, angular fragments. In other pipes, as the Old Reliable, Globe, and Superior, well-rounded fragments are common, though angular fragments are present. The association of angular and well-rounded fragments with alteration bands paralleling the surface of both, indicates a common origin for angular and rounded fragments.

5. In some pipes, the dissolving action was more intense than deposition, resulting in open or incompletely cemented breccia.

6. Locally in some pipes, faults of sufficient magnitude are present to form a true fault breccia.

7. Some slumping occurred after formation of the replacement breccia and caused local crushing of gangue and ore minerals and rotation of some fragments.

8. Pipes like the American Eagle represent an early stage of brecciation, whereas those that are entirely silicified represent a final stage of alteration.

ORE DEPOSITS.

History and Production.—As early as 1863, rich lead-silver ore from the Blue Bird mine was shipped by way of Yuma and the Colorado River to Swansea, Wales. Prior to this, the region was prospected for silver by the Spaniards and Mexicans. In 1883, three years before the surrender of Geronimo ended the Apache problem in southern Arizona, the region was organized as the Bunker Hill Mining District.

In 1903, the Copper Creek Mining Company acquired claims along Copper Creek. Its successors, the Minnesota-Arizona Mining Company and the Copper State Mining Company prospected numerous pipes and produced some copper ore. In 1907, the Calumet and Arizona Mining Company bought two groups of claims from Clark and Scanlon and prospected a large group of pipes, which included the Copper Prince, Globe, and Superior. In 1933, the Arizona Molybdenum Corporation purchased the Childs-Aldwinkle property and produced molybdenum and copper

ore until the fall of 1938 when lessees took over the property and worked it until the fall of 1939.

The known production of the Copper Creek region up to 1939 is:

Mine.	Lbs. Molybdenite.	Lbs. Copper.	Lbs. Lead.	Ozs. Au.	Ozs. Silver.	Estimated Production.
Childs-Aldwinkle	6,946,782	5,859,033	—	723	26,938	—
Blue Bird to 1920	—	—	—	—	—	$150,000
Blue Bird, 1926–39	—	200,000	4,000,000	—	119,000	
Copper Prince, 1937	—	1,227,667	—	—		—
Clark Scanlon, 1905–30	—	200,000	—	—	15,000	—
Copper State Metals, 1905–16	—	700,000	—	—	55,000	—

Types of Ore Deposits.—The ore deposits in the Copper Creek region may be classified as breccia pipe and vein deposits. The production has been largely from pipes, notably the Childs-Aldwinkle, the Copper Prince, the Old Reliable, the American Eagle, and the Globe. Numerous other pipes were prospected, but failed to yield ore. The productive pipe deposits are either in, or close to the granodiorite. Many veins have been prospected, several show strong mineralization, but only one, the Blue Bird, has proved commercial. The Blue Bird vein, like the productive pipe deposits, is within the granodiorite. Most vein deposits, including the Blue Bird, are in the N. 60° E. system of faults. The ore minerals of the veins differ from the pipe deposits. The metals most common in the veins are lead, silver, and copper, whereas molybdenum and copper are most important in the pipes.

Zoning of the Metals.—A rough lateral zoning of metals exists in the Copper Creek region. Molybdenite appears to be restricted to a small area less than one mile in diameter, which includes the Childs-Aldwinkle, Old Reliable, Copper Prince, and several smaller pipes east and south-east of the Childs-Aldwinkle mine. Copper in this central area exceeds molybdenum in amount. Outside the molybdenum-copper center is a zone in which copper minerals predominate, and surrounding this is a zone that includes the lead-silver-copper deposits of the Blue Bird mine and several smaller lead-copper deposits. The area including the molyb-

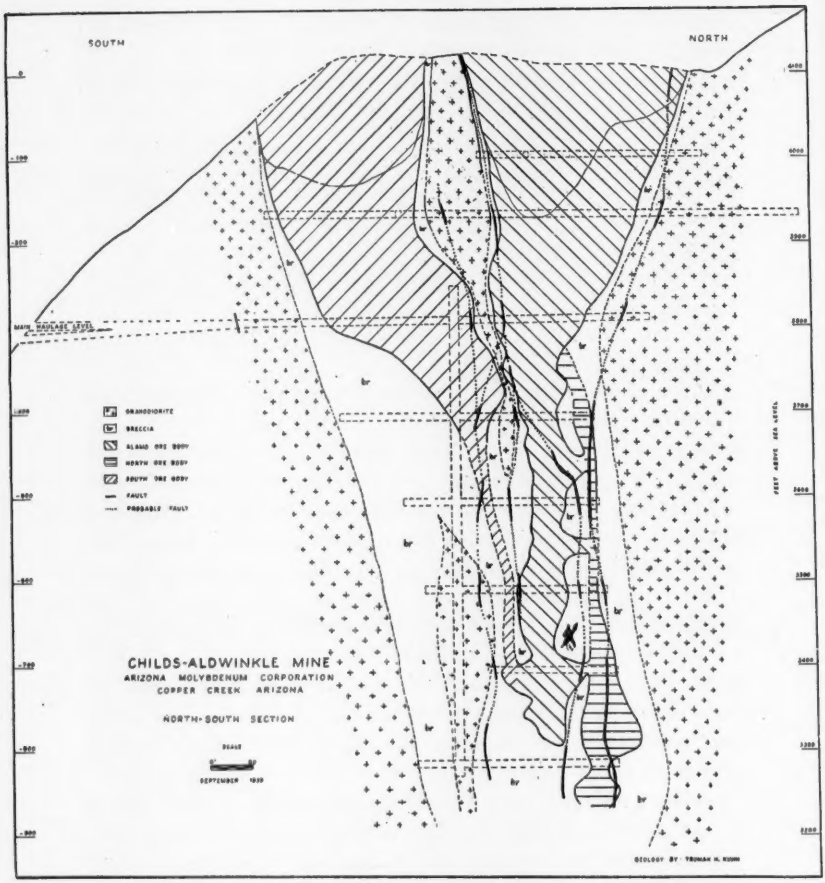


FIG. 7. North-south section through Childs-Aldwinkle mine.

denum, copper, and lead zones is approximately 2 miles in diameter.

Age of Mineralization.—The age of the mineralization cannot be established but it is assumed that it took place after the emplacement of the granodiorite and the extrusion of the basalt.

Breccia Pipe Deposits of the Childs-Aldwinkle Mine.

The ore bodies of the Childs-Aldwinkle mine are in the breccia pipe described under that name (Fig. 7). In the upper levels of the mine, the main bodies of ore are at the peripheries of the breccia mass, but with depth the ore bodies become smaller and are near the center of the pipe. The south ore body, occupying the southern branch of the pipe, is considered a branch of the main ore body in the northern pipe, which it joins at a depth of about 700 feet. Although the ore in the northern ore body cuts off at 800 feet in depth, exploratory work shows that sulphide mineralization persists for at least another 70 feet. From the 400- to 500-foot levels a small body of ore 25 feet north of the main ore body was followed downward to a large body on the 750-foot sub-level. This body changes from the vertical to a dip of 65° E. At the bottom of the mine (850 feet), this northern ore body follows a north-south fault along which the oval outline becomes much elongated. In a shallow winze sunk in this fault, the molybdenum and copper mineralization changes to a vein of pyrite 2 to 3 feet wide. Faults striking north-south control the shape and trend of the ore bodies or are intimately associated with the bodies of ore in the breccia pipe. The other major fault systems striking east-west, N. 60° E., and N. 70° W., so strongly present in the pipe, play only a minor role in controlling ore deposits.

Hypogene Minerals.—Molybdenite is fairly constant in amount throughout the mine but the appearance changes appreciably. In the upper levels, flakes and crystals averaging one-quarter inch in width, replace the rock and fill spaces between quartz crystals. At depth, rosettes become common, and in the lower parts of the mine some attain a diameter of one and one-half inches. Well-formed, flat, hexagonal crystals of molybdenite fill some of the open spaces on the 300- and 400-foot levels.

Molybdenite is the latest sulphide mineral in the Childs-Aldwinkle mine and is later than many gangue minerals. Above the 400-foot level, some molybdenite has been deposited on quartz, pyrite, and chalcopyrite crystals. Throughout the mine, molybdenite occurs as masses and rosettes replacing pyrite, bornite, ten-

nantite, chlorite, sericite, quartz, and orthoclase. Seen in polished sections, long delicate fingers of molybdenite replace other sulphides and gangue minerals (Fig. 8). Molybdenite also develops along boundaries between gangue and metallic minerals and is wrapped around quartz and pyrite crystals.

The production table shows that the copper recovered from the Childs-Aldwinkle ores is about equal in amount to the molyb-

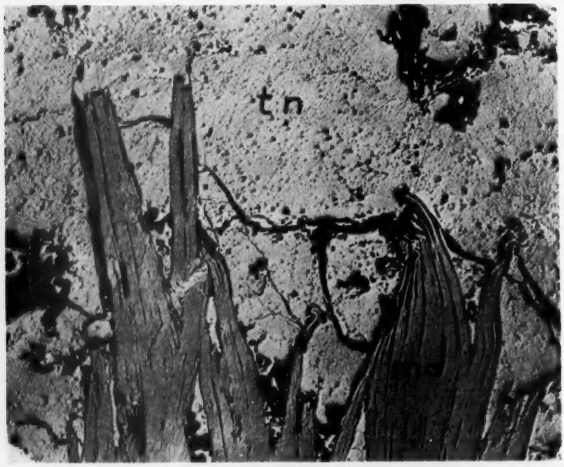


FIG. 8. Molybdenite replacing tennantite, Childs-Aldwinkle mine. 800-foot level. × 50.

denum, but distributed differently. The molybdenite content is fairly constant at 1 to 2 per cent; the copper content ranges from 1 per cent in the upper levels, to 6 to 8 per cent at 800 feet below the surface, and to less than 2 per cent at the bottom of the mine.

The copper minerals also change with depth. Near the surface, bornite is in small amounts but increases with depth, and at 800 feet below the surface is the main copper mineral. Chalcopyrite is common near the surface but more abundant at depth. Tennantite first appears at 200 feet below the surface but does

not become important above the 700-foot level. Below 700 feet it is one of the important ore minerals. Chalcocite is a minor mineral in the lower levels and enargite is present in minute amounts intergrown with tennantite.

The order of deposition of the copper minerals is, chalcopyrite. bornite, chalcopyrite, chalcocite, enargite, tennantite.

No sharp age relation exists between bornite and chalcopyrite. In many polished sections of the ore from the lower levels, bornite replaces chalcopyrite along gangue-chalcopyrite boundaries and as irregular veinlets in the chalcopyrite. The bornite protrudes from the veinlets as small barbs, all oriented in the same direction. In the same sections chalcopyrite replaces bornite along boundaries and as irregular veinlets in bornite. Another common texture is long blades of chalcopyrite oriented along crystallographic directions in the bornite. These extend from irregular veinlets of chalcopyrite cutting bornite. A more common chalcopyrite-bornite relation is smooth curved boundaries with no decided projections of one mineral into the other, or the "mutual boundary texture." Many believe that this texture is indicative of contemporaneity, but it has been produced artificially by replacement.[14]

Chalcocite is present in the polished sections of the ore from the lower levels of the mine as irregular veinlets and embayments in bornite strongly reminiscent of the familiar "exploded bomb" structure of pyrite. The boundary between bornite and the replacing chalcocite is extremely fuzzy. In places, the pale bluish-gray color of chalcocite and the pinkish-brown color of bornite is separated by a narrow pale blue band which probably represents a transitional stage in the replacement of bornite by chalcocite.

Tennantite replaces bornite, chalcopyrite, and chalcocite, usually as veinlets with sharp, irregular boundaries. It also occupies boundaries between bornite or chalcopyrite and gangue. Enargite, in the few places it has been observed, is associated with tennantite, generally as intergrowths representing simultaneous development.

[14] Newhouse, W. H.: The microscopic criteria of replacement in the opaque ore minerals. In Fairbanks, E. E. (Editor), The Laboratory Investigations of Ores, McGraw-Hill Book Co., pp. 160–161, 1928.

Pyrite crystals and massive pyrite are common throughout the Childs-Aldwinkle mine with but little change in amount and character. It is the earliest sulphide. Chalcopyrite has replaced it most commonly, but all other sulphides have been observed replacing pyrite.

Galena and sphalerite are rare. Light brown sphalerite, exceptionally free of iron, is present in one hand specimen. Insufficient quantities of galena and sphalerite are present to definitely establish their relationship to the copper minerals, but replacement evidence suggests that galena is later than sphalerite and both are later than tennantite.

Supergene Minerals.—Supergene enrichment is not important at the Childs-Aldwinkle mine. The typical supergene minerals, ferromolybdite, malachite, azurite, cuprite, covellite, and chalcocite are found near the surface of the pipe. In addition, small amounts of the deeper bornite, chalcopyrite and chalcocite are considered supergene.

The mineral sequence may be summarized, starting with the earliest, as follows: Hypogene—pyrite, chalcopyrite, bornite, chalcopyrite, chalcocite, enargite, tennantite, sphalerite, galena, molybdenite. Supergene—chalcopyrite, bornite, chalcocite, covellite, azurite, malachite, cuprite, ferromolybdite, "limonite."

Gangue Minerals.—The gangue minerals at the Childs-Aldwinkle mine show a change with depth. Quartz is found at all levels, but it is more abundant in the upper levels where it is commonly massive with crystals only in the vugs. With depth, crystals of quartz become more common and increase considerably in size.

Sericite occurs in the upper levels in small quantities and increases in abundance with depth until on the 820-foot level the central portion of the pipe is composed chiefly of sericite.

Chlorite is uncommon near the surface. In the intermediate levels, fine-grained chlorite is the principal gangue mineral. With depth, the chlorite becomes coarser until at 780 feet below the surface some chlorite plates are over 2 inches across. The chlorite at the bottom of the mine is coarse, with an average grain size of

one-half inch. Some tourmaline occurs with the coarse grained chlorite.

Orthoclase is present in the pegmatitic zone at the bottom of the Childs-Aldwinkle mine as anhedral crystals up to 6 inches long. It is present as high as the 300-foot level as well-formed crystals, one-quarter inch in diameter, lining open spaces, but orthoclase was not observed near the surface.

Apatite is confined to the lower and intermediate levels. On the 820-foot level, crystals one-half to three-quarter inch across are common, and one crystal 5 inches long was found. Above this level, the crystals become smaller, and on the 300-foot level they are only one-eighth to one-sixteenth inch across.

Relation of Metallic to Gangue Minerals.—With but few exceptions, the metallic minerals of the Childs-Aldwinkle mine are considered later than the gangue minerals. Molybdenite developed in fine-grained chlorite and sericite. The early copper minerals replace orthoclase along cleavage planes and fill open spaces in which quartz and chlorite crystals had developed. In a few specimens from the lower levels, a later quartz cuts all sulphides except molybdenite. Calcite and gypsum appear to be deposited by descending waters and are later than the hypogene sulphides.

The Ore.—Grains and masses of sulphides disseminated in the gangue surrounding the granodiorite blocks of breccia constitute the typical ore of the Childs-Aldwinkle mine. Sulphides, to some extent, replace the granodiorite, but pyrite is the only one that has penetrated deeply, and then only in small, scattered grains.

The change in gangue minerals produces notable differences in the appearance of the ore. In the upper levels, the sulphides generally occur in a dense, white quartz with some sericite, but in the intermediate levels, they are in a soft, crumbly, fine-grained chlorite. In the pegmatitic zone the sulphides replace quartz and orthoclase and fill spaces between chlorite crystals. On the 820-foot level, some sulphides are in a very soft and crumbly sericite.

Alteration of the granodiorite host rock has been discussed under zoning of the Childs-Aldwinkle pipe. As the pipe is approached, alteration is apparent in a progressive increase in

chlorite, sericite, quartz, apatite, and magnetite; and a decrease in biotite, pyroxene, and feldspars. The amount of kaolin increases as the pipe is approached, but thin sections of granodiorite from inside the pipe show little kaolin.

Classification of the Deposit.

The mineralization at the Childs-Aldwinkle mine differs only in details from other molybdenum deposits.

At Climax, Colorado, molybdenite, pyrite, chalcopyrite, sphalerite, quartz, orthoclase, hubnerite, fluorite, and sericite, are present in a pipe deposit that Butler and Vanderwilt [15] suggest might be mesothermal.

In appearance, a portion of the Childs-Aldwinkle ore is similar to the ore from the New Cornelia mine at Ajo, Arizona, where chalcopyrite, bornite, chalcocite, pyrite, molybdenite, sphalerite, tennantite, hematite, and magnetite, are distributed along two zones of pegmatitic alteration. In these zones the monzonite host rock is replaced by quartz and orthoclase, the latter up to several inches across. Some coarse-grained chlorite accompanies the pegmatitic zones.[16]

At Cananea, Sonora, Mexico, Kelley [17] has reported molybdenite, pyrite, chalcopyrite, bornite, chalcòcite, covellite, tennantite, galena, sphalerite, quartz, phlogopite, kaolin, and alunite. Molybdenite, according to Kelley, is one of the early minerals and is hypothermal. The later pyrite, galena, sphalerite, tennantite, covellite, and chalcopyrite are mesothermal.

At Bingham, Utah, molybdenite, pyrite, chalcopyrite, bornite, covellite, chalcocite, with traces of pyrrhotite, arsenopyrite, tetrahedrite, galena, sphalerite, quartz, orthoclase, biotite, and much sericite are present in a mesothermal deposit.

[15] Butler, B. S., and Vanderwilt, J. W.: Climax molybdenum deposit. U. S. Geol. Surv. Bull. 846–C: 233–235, 1931.

[16] Gilluly, James: Geology and ore deposits of the Ajo quadrangle, Arizona. Ariz. Bur. Mines, Geol. Ser. No. 9, Bull. 141: 79–80, 1937.

[17] Kelley, V. C.: Paragenesis of the Colorado copper sulphides, Cananea, Mexico. ECON. GEOL., 30: 663, 1935.

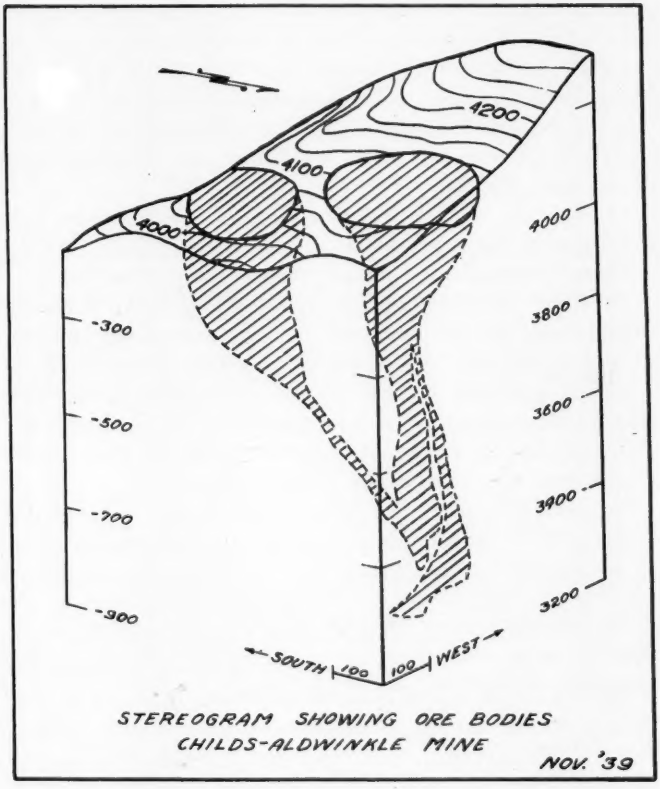


FIG. 9. Sterogram showing ore bodies at Childs-Aldwinkle mine.

Buddington [18] has described a deposit at Shakon, Alaska, consisting of an early pegmatitic stage of orthoclase, followed by quartz and pyrite, adularia, a sulphide period of pyrite, sphalerite, pyrrhotite, and chalcopyrite, then molybdenite, followed by a zeolite and chlorite stage. Buddington believes the pegmatitic and

[18] Buddington, A. F.: Molybdenite deposit at Shakon, Alaska. ECON. GEOL., 25: 197–200, 1930.

adularia stages are hypothermal, the sulphide minerals mesothermal, and the zeolite and chlorite stage epithermal.

Hess[19] has described numerous small molybdenite deposits associated with pegmatites and minerals usually considered to be high temperature, such as cassiterite, wolframite, and garnet, but states that the molybdenite was probably deposited after the solidification of the pegmatitic dikes.

At the Valley of Ten Thousand Smokes, Alaska, molybdenite was deposited in a steam vent at a temperature of 264° C.[20] which is within Lindgren's mesothermal range.

Peterson[21] has described a molybdenum deposit at Mammoth, Arizona, only 11 miles west of Copper Creek. Here, wulfenite, which Peterson believes is hypogene, is one of the latest minerals to form. Wulfenite, with various vanadium and manganese minerals, has been introduced as a fourth stage of mineralization following the deposition of quartz, specularite, chlorite, pyrite, sphalerite, galena, fluorite, chalcopyrite, and gold.

The mineralization at the Childs-Aldwinkle mine is thus similar to that of other mesothermal deposits and the minerals are typical of the intermediate temperature range. The deposit is, therefore, regarded as mesothermal. The coarse crystallization at the Childs-Aldwinkle mine suggests slow crystallization either at depth or under an impervious cap that permitted only a slow dissipation of heat and pressure.

UNIVERSITY OF ARIZONA,
TUCSON, ARIZ.,
Jan. 2, 1941.

[19] Hess, F. L.: Molybdenum deposits. U. S. Geol. Surv. Bull. 761, 1924.

[20] Zeis, E. G.: The Valley of Ten Thousand Smokes. National Geographic Society, vol. 1, Katmai Series, No. 4: 28–30, 1929.

[21] Peterson, N. P.: Geology and ore deposits of the Mammoth mining camp area, Pinal County, Arizona. Ariz. Bur. Mines, Geol. Ser., No. 11, Bull. 144: 43–54, 1938.

MINERALIZATION AT THE POLARIS MINE, IDAHO.

MAX E. WILLARD.

ABSTRACT.

The veins of the Polaris mine of the Coeur d'Alene mining district are of hydrothermal origin, formed at intermediate temperatures and depths. The mineralogy and paragenesis are discussed. The occurrence of gersdorffite, a mineral not previously recognized in the ore of the "Silver Belt," is established. The evidence suggests that the vein minerals were deposited in a rather definite and non-recurrent but interrupted sequence. Structural adjustments concurrent with the mineralization controlled the localization of ore.

INTRODUCTION.

THE Polaris mine is located in the "Silver Belt" of the Coeur d'Alene mining district of Idaho, about five miles northwest of Wallace. Silver ore occurs in veins between the Polaris and Big Creek faults in a subsided block of the pre-Cambrian Belt series.[1] The mine was operated intermittently from 1884 to 1934, and continuously by the Hecla mining company since then. The Polaris vein is exposed through a vertical range of 1500 feet.

This growing mine is the second largest in the "Silver Belt" and a description of its ores may prove of interest.

The author is indebted to Dr. Alfred L. Anderson of Cornell University for many suggestions during the course of this study and for his helpful criticism of the manuscript. The author is also grateful to Mr. James F. McCarthy, President of the Hecla Mining Company, for the privilege of examining the Polaris mine. To Dr. R. Balk, Dr. L. W. Currier, and Mr. R. H. Jahns thanks are also due for their helpful criticism of the manuscript.

[1] Ransome, F. L., and Calkins, F. C.: The geology and ore deposits of the Coeur d'Alene district, Idaho. U. S. Geol. Surv. Prof. Pap. 62, pp. 62–63, 1908.

GENERAL GEOLOGY AND STRUCTURE OF THE VEINS.

The rocks of the Coeur d'Alene district include a thick series of folded and faulted sediments of the pre-Cambrian Belt series, of which only the St. Regis and over-lying Wallace formations occur in the area of the mine. These formations consist of 5000 to 6000 feet of interbedded quartzitic sandstones and calcareous shales.[2] The rocks of these formations have been strikingly bleached, along an east-west zone at least 2000 feet wide, to light greenish or mottled greenish-gray and black varieties. All gradations from the original rock to bleached rock may be observed. At the mine the unbleached beds are thin and dense, and range from black to light gray in color. Microscopic examinations show fine-grained calcium, magnesium, and iron carbonates, with subordinate amounts of pyrite, magnetite, garnet and quartz. Similar studies of the bleached rocks showed them to be composed almost entirely of sericite, which progressively replaced the original rock minerals, indicating alteration by hydrothermal solutions rich in potassium.

The Polaris, Chester and Silver Summit are the principal veins now being explored by the company in the "Silver Belt." Of these veins, only the Polaris has yielded commercial ore. The other two where exposed are barren carbonate veins.

The Polaris vein lies in the intensely bleached and sericitized zone. It strikes north 87° E. and dips 72° S. It occupies a complexly fractured zone consisting of a main fissure with numerous adjacent minor fractures. Along its strike and dip the vein pinches and swells from a fraction of an inch to several feet in width, due to movement along an irregular fracture surface that brought into juxtaposition parts of walls whose original positions were some distance apart.

The Chester and Silver Summit veins are nearly parallel and strike north 75° to 80° E. and dip steeply to the south. The Chester lies about 2700 feet north of the Polaris on the 1000 foot level, and occupies a fissure in the Wallace formation outside of the bleached zone. The Silver Summit vein is from 2000 feet

[2] Ransome and Calkins: *op. cit.*, pp. 23–25.

to 3000 feet southeast of the Polaris and within the altered sheared zone.

Character of the Ore.—Silver is the metal of chief value in the Polaris. The ore contains little or no zinc, and lead and copper are of secondary importance. Nickel, which has not been previously reported in the ore of the area, occurs sparingly.

A slight vertical zoning is evident in the deposit. Lead occurs throughout the vein but is most abundant below the 200 foot level, as are copper and silver. Nickel is not present in the ore above the 900 foot level but becomes conspicuous with increasing depth.

DESCRIPTIVE MINERALOGY.

The hypogene minerals of the veins are pyrite, gersdorffite, arsenopyrite, tetrahedrite, chalcopyrite, bournonite, galena, and boulangerite, with siderite, ankerite, calcite, and quartz. Proustite, anglesite, and cobalt bloom are supergene minerals.

Pyrite.—Pyrite is ubiquitous throughout the ore of the mine. It possesses variable characteristics and is evidently not all of the same age.

Some of it occurs as massive aggregates or as irregular or rounded grains enclosed in siderite and tetrahedrite. Some of the pyrite masses are cut by irregular veinlets of tetrahedrite with non-matching walls and others are shattered and cemented by siderite (Fig. 1). In no place does this shattered pyrite have definite crystal outlines. Pyrite also occurs in the upper levels as small lustrous euhedra disseminated through the siderite, and in quartz druses.

Pyrite occurs also as residual grains in the other sulphides. Its mode of occurrence and general relations indicate that it was deposited during three distinct stages, some older and some younger than the other sulphides. Under the microscope, the pyrite shows in part an anomalous weak anisotropism, with yellowish-brown to blue polarization colors.

Gersdorffite.—Specimens collected from the lower levels of the mine contain a mineral that appears to be gersdorffite. It occurs as small irregular grains that do not exceed 50 microns in

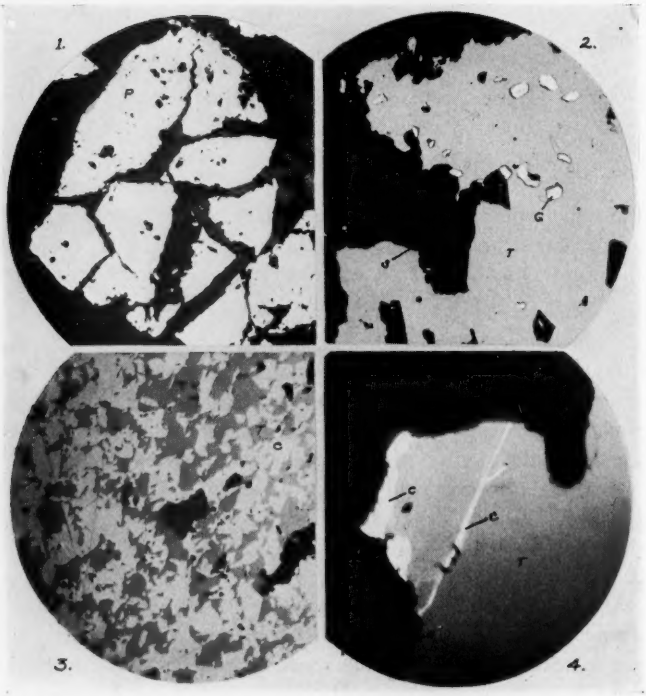


FIG. 1. Massive pyrite (P) showing shattering and subsequent filling of fractures by siderite (gray) and replacement of both by quartz (black).

FIG. 2. Gersdorffite (G) disseminated in tetrahedrite (T); some grains show the beginning of replacement by tetrahedrite.

FIG. 3. Chalcopyrite (C) and tetrahedrite (T) in typical relations.

FIG. 4. Incipient veinlets of chalcopyrite (C) replacing tetrahedrite (T) and irregular embayments of tetrahedrite in siderite (black).

diameter. On polished surfaces, it has a pinkish white color and appears to be slightly softer than pyrite. It is isotropic and reacts negatively to all etch tests listed by Short.[3] Microchemical tests

[3] Short, M. N.: Microchemical determination of the ore minerals. U. S. Geol. Surv. Bull. 914, 1940.

revealed that the mineral contains nickel, iron and arsenic. Qualitative chemical tests on fragments of the ore known to contain the mineral showed a considerable amount of nickel and small amounts of cobalt. The mineral, therefore, is probably a sulpharsenide of nickel, iron and cobalt, which suggests that it is an isomorphous mixture of gersdorffite and cobaltite molecules with a hypothetical sulpharsenide of iron.

Prior to the author's identification, gersdorffite has not been recorded from the ores of the "Silvert Belt."[4] It has, however, been reported by Shannon[5] in the ore of a prospect near Avery in the St. Joe region, Idaho.

Gersdorffite was not found in the ore above the 900 level, but increases in amount from that level down. Most of it is disseminated in the siderite, but some occurs as irregular grains in tetrahedrite. These grains are generally rounded and show evidence of replacement. (Fig. 2).

Tetrahedrite.—Tetrahedrite is the most abundant sulphide in the ore and contains most of the silver. It occurs throughout the vein, but appears to increase in amount with depth. In the Polaris ore it contains 5.4 per cent silver and is, therefore, freibergite.

An arsenical and mercurical variety of tetrahedrite reported in the ore by Ransome and Calkins[6] could not be verified. Quantitative chemical analysis of the mineral revealed only 0.76 per cent arsenic, and no mercury was detected. A spectrographic analysis also failed to detect the presence of mercury. A small quantity of bismuth was detected in both the chemical and spectrographic analyses.

The mineral commonly contains numerous angular inclusions of siderite (Fig. 2) and small veinlets of it occur along siderite cleavages.

[4] Willard, M. E.: Masters thesis, University of Idaho, pp. 8–9, 1938.

[5] Shannon, E. V.: The minerals of Idaho. Smithsonian Inst., U. S. Nat. Museum, Bull. 131, p. 135, 1926.

[6] Ransome and Calkins: *op. cit.*, p. 93.

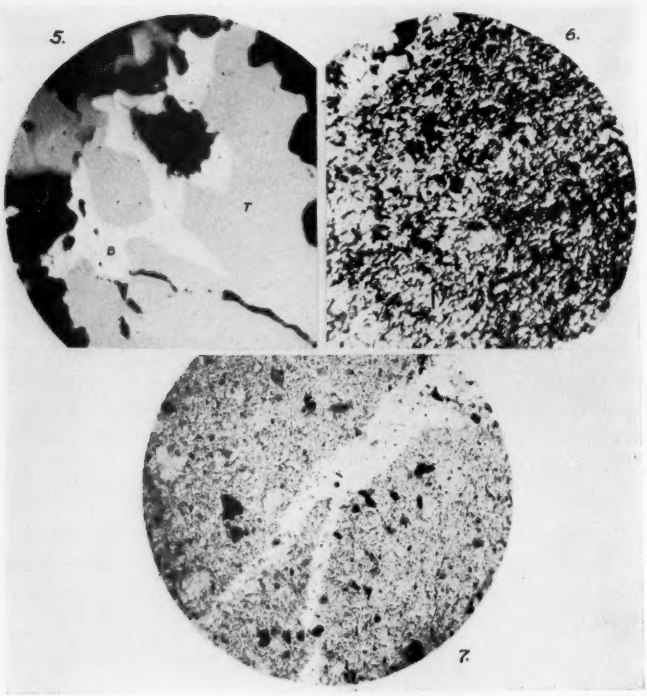


FIG. 5. Bournonite (B) replacing tetrahedrite (T) as indicated by contact "caries" convex to tetrahedrite.

FIG. 6. Felted intergrowth of anglesite (gray) in massive galena (white).

FIG. 7. Wall rock showing advanced silicification. Shagreen areas principally quartz, cut by veinlet of later clear quartz.

Arsenopyrite.—Arsenopyrite was reported by Shenon [7] to be fairly abundant in the ore, but none was found in the specimens collected by the writer.

Chalcopyrite.—Minor amounts of chalcopyrite are associated with tetrahedrite. Where the grains are large, its contacts are

[7] Shenon, P. J.: Personal communication.

generally convex towards tetrahedrite (Fig. 3). Some of it, however, occurs as minute veinlets within the tetrahedrite or along the grain contacts of siderite and tetrahedrite (Fig. 4). Some veinlets in tetrahedrite are cut off by galena. Therefore, it appears to be younger than the tetrahedrite, but older than the galena. It does not appear to replace gangue minerals.

Bournonite.—The occurrence of this sulphantimonide of lead and copper is believed to be definitely established by etch reactions and microchemical tests. The mineral occurs principally as irregular grains in the tetrahedrite and shows distinct caries convex towards tetrahedrite (Fig. 5). In several places, however, the relations are not clear because the minerals have developed mutual boundaries. These relations are interpreted as indication of overlap in the deposition of the two, but with bournonite in part the younger. The only other occurrence of bournonite recorded in the Coeur d'Alene district is that reported by C. H. Rasor and R. J. Anderson at the Sunshine mine.

Galena.—Galena is sparingly distributed through the vein proper, but is abundant as massive aggregates, which exhibit flowage structure, in subordinate fractures that extend out from the main vein. It also occurs along grain contacts between siderite and pyrite, and as reticulating veinlets along cleavage planes in siderite. Opposite walls of these veinlets do not match, indicating that the galena replaces the siderite. Small veinlets of galena, at and above the 600 level, appear to have been altered to a fibrous or felted mass of anglesite.

Boulangerite.—Boulangerite was found in the Chester vein in the form of needles or fibrous masses associated with residual inclusions of siderite and quartz.

Siderite.—Siderite is the principal gangue in the Polaris and Silver Summit veins, but is sparse in the Chester. It is invariably coarse-grained, massive, and has a typical light tan or buff color. Surfaces after exposure generally turn black or reddish-brown because of the oxidation of iron and manganese.

The siderite of the two veins has the following composition:

	Polaris	Silver Summit
$FeCO_3$	83.1	80.7
$MgCO_3$	7.7	10.3
$CaCO_3$	0.7	0.4
$MnCO_3$	8.6	8.6
	100.1	100.0

It is commonly cut by irregular, ramifying veinlets of quartz, which in places followed the cleavage of the siderite. At other places the quartz veinlets intersect each other in reticulated pattern, enclosing residual rhombs of siderite. Similar relations also exist between siderite and tetrahedrite, but irregular grains of siderite in sulphides are common. Therefore, it appears that the siderite was once much more abundant, and that a large part of it was subsequently replaced by gangue and ore minerals.

Ankerite.—Ankerite is confined mainly to the Chester vein. In places it is cut and partly replaced by veinlets of siderite, but elsewhere the relations are indefinite, perhaps indicating an overlap in deposition. In other places, the ankerite has been brecciated and the fractures subsequently filled with quartz. Its composition is:

$FeCO_3$	34.5
$MgCO_3$	14.7
$CaCO_3$	47.2
$MnCO_3$	3.6
	100.0

Quartz.—Quartz is the main gangue mineral of the Polaris vein, but is sparse in the Silver Summit and Chester veins. It is present in three distinct forms in the Polaris, *i.e.*, as massive quartz, as a milky comb quartz, and as clear granular quartz.

Massive white quartz is most abundant. Its contacts with siderite are angular because they follow the cleavages of the siderite. It contains numerous residual inclusions of siderite and in turn is veined and partly replaced by sulphides, but some of it fills fractures in massive pyrite. Some also fills fractures in the carbonates. In the Chester vein this type of quartz occurs in fractures that extend from wall to wall, simulating a ladder ar-

rangement. Late, clear, granular quartz occurs in small amounts, associated with galena.

Supergene Minerals.—Proustite, anglesite, and erythrite are the reported supergene minerals of the deposit. Proustite is said to have been present in some of the ore shipped from the mine, but Calkins, who examined the mine in 1905, did not confirm its presence. None was found in the ore examined by the author. A mineral that appears to be anglesite occurs in felted masses along the walls of galena veinlets (fig. 6). The identity of the mineral is not definitely established, but microchemical tests indicate that it contains considerable lead. Shenon reports that erythrite occurs in openings in the ore of the upper levels, but none was present in the specimens collected by the writer.

WALL ROCK ALTERATION.

The principal veins of the deposit lie in the belt of extensively bleached and sericitized rock previously described, upon which is superimposed the vein alteration. The latter, which rarely extends more than a few feet on either side of the veins, was largely an introduction of pyrite, siderite, and quartz.

Immediately adjacent to the veins is a narrow band of light-gray, fine-grained, tough rock made up almost entirely of quartz of two generations. The first generation is fine-grained, cloudy, and contains many residual inclusions of sericite and siderite. The second generation is fine-grained and clear. This clear quartz occurs as bifurcating veinlets along small fractures in the earlier quartz (Fig. 7).

The zone of light-gray rock grades outward into a fine-grained, greenish-buff colored rock. It is made up largely of siderite, which contains microscopic residual grains of sericite, the distribution of which commonly outlines the original foliaton of the country rock.

Pyrite is the most widespread mineral in the altered wall rock. It is partly associated with the siderite, but also extends into the sericitized country rock for several feet, where it occurs as minute euhedra aligned along the foliation.

PARAGENESIS.

The minerals of the Polaris and associated veins show evidence of having been deposited in a definite but interrupted sequence. The earliest deposited sulphide is pyrite, and its deposition was followed by slight shattering. Next, ankerite, and then siderite were deposited, along with disseminated euhedra of second generation pyrite. Perhaps the gersdorffite was deposited at about the same time, for it occurs in the siderite and in the tetrahedrite. The deposition of these carbonates and associated minerals temporarily closed the channel-ways to the mineralizing solutions.

Further fracturing occurred, however, followed by the deposition of massive white quartz, which was deposited partly as a drusy filling, but mostly by replacement of the earlier carbonates. Pyrite deposition ended this stage. Subsequent minerals were introduced only after still later fracturing had re-opened the channels, as in the Polaris vein, where mineralization continued. Tetrahedrite was apparently the first mineral deposited at this time for it has replaced all of the earlier minerals in the sequence and has been replaced by most of the later sulphides. Bournonite was deposited in part with the tetrahedrite, and galena after the chalcopyrite. Boulangerite apparently was deposited after siderite and quartz. At the Silver Crescent mine, several miles to the northwest, boulangerite is reported to have replaced galena.

This final stage of mineralization was closed with the deposition of minor amounts of clear granular quartz. Although the evidence is inconclusive, it appears likely that a small amount of late calcite was also deposited since it occurs in small cavities in galena.

DIAGRAM SHOWING THE SEQUENCE OF MINERALIZATION AT THE POLARIS MINE.

SUMMARY AND CONCLUSIONS.

The veins of the Polaris mine are of hydrothermal origin, but the source of the mineralizing solutions is as yet unknown. The hydrothermal origin is indicated by the occurrence of group replacements, granular intergrowths, replacement in part independent of fractures, abundant sericite, and replacement of both gangue and sulphides by the same minerals. Texture and mineralogy indicate that the veins are mesothermal, but the drusy cavities and comb-structures in the quartz, particularly in the upper portions of the veins, suggest that the lodes belong to the upper part of the mesothermal zone. The deposit should be classified as a tetrahedrite-siderite vein.

The localization of ore was controlled chiefly by the existence of satisfactory channelways for the circulation of the metallizing solutions, and stresses concurrent with deposition that kept the channels open to receive ore.

Ransome and Calkins[8] describe the Polaris vein as a simple fissure filling but their observations were limited because of the lack of extensive mine workings. The portion of the vein now exposed shows, however, that comb-structure, vugs, crustification, and other features of cavity filling, although not completely absent, are on the whole exceptional. On the other hand, evidence of extensive replacement is plentiful. It is believed, therefore, that the Polaris and nearby veins are mainly lode replacements of the altered country rock.

The minerals of the Polaris vein have been deposited in a rather definite and non-recurrent but interrupted sequence. Deposition was not continuous but, as ore filled and choked available openings, the flow of solutions was obstructed and deposition ceased until structural disturbances reopened the channels and permitted further flow of the mineralizing solutions. The Polaris vein shows evidence of having been opened at least twice, once just after the deposition of siderite, and again after the deposition of quartz. The valuable sulphides of the ore have all been de-

[8] Ransome and Calkins: *op. cit.*, p. 188.

posited later than the quartz. The parts of the Chester and Silver Summit veins examined by the writer were not reopened after the deposition of the quartz, and, in consequence, contain no ore.

The mineralization at the Polaris was comparatively uniform through a considerable vertical range, and may be expected to continue to greater depths without great change. The slight mineralogical variations that occur with increasing depth, such as the decrease in quartz content, the apparent increase in the amount of ore minerals, and the appearance of gersdorffite and bournonite, suggest a primary vertical zoning.

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March 15, 1941.

DRILLHOLE PROBLEMS IN THE STEREOGRAPHIC PROJECTION.

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ABSTRACT.

Methods for the solution of drillhole problems involving buried tilted beds (veins, faults) by means of the stereographic projection are herewith outlined.

DERIVATION of the trigonometric formula involved in the solution of the two-drillhole problem (where one hole is vertical) to elucidate the structure of buried tilted beds (veins, faults) lacking recognizable marker horizons appears in a recent issue [1] of this JOURNAL. By means of the stereographic projection the four problems given were solved graphically in about an hour, and after doing the first one (which involved developing the method) the remainder were done in not over five minutes each. Moreover, the graphical solution immediately brought out an error in problem I.

The writer has elsewhere pointed out the value of this projection in handling the two-tilt problem,[2] but the use of the meridian stereographic net there described is not suitable for the solution of the present problem. An article is in press [3] describing both stereographic and gnomonic projections together with the four general types of problems (distance, angle, rotation, and reflection) that can be handled to advantage with them. Practically all problems that can be solved by spherical trigonometry where a solution to within 1° is satisfactory fall in this category. All crystallographers are familiar with these projections, as problems involving lines (directions) and planes in their various angular relationships are legion in this field. But in spite of the fact that most crystallography is

[1] Stein, Herbert A.: A trigonometric solution of the two-drillhole problem. Econ. Geol., 36: 84–94, 1941.

[2] Fisher, D. Jerome: Problem of two tilts and the stereographic projection. A. A. P. G. Bull., 22: 1261–1271, 1938. Also see *Idem.*, 23: 683–685, 1939.

[3] Fisher, D. Jerome: A new projection protractor. Jour. Geol., 49: Nos. 3 and 4, 1941.

taught in or closely associated with geological departments in this country, geologists as a class are ignorant of the potential uses of these projections in the structural field.

For simplicity the writer reproduces herewith the four problems of Stein, and two additional problems to illustrate the more general case where both drillholes are off vertical. In this connection it should be noted that few such holes are vertical, although some shallow ones may attain this ideal. In case the attitude of the supposedly vertical hole is measured at the point that furnishes the core studied, if it is found not to be vertical the solution goes over to the more general category of two inclined holes. The writer uses Stein's symbols, as follows:

H = vertical angle of dip of the inclined drillhole,
V = core-bedding (vertical) angle in the vertical drillhole core (this is the complement of the dip angle of the beds),
I = core-bedding (vertical) angle in the inclined drillhole core,
D = true dip of the beds—given as vertical angle and bearing (the latter is normal to the strike).

PROBLEM I.

$H = 60°$ to N. 5° E.; $V = 50°$; $I = 20°$; $D =$ ———?

In the stereographic projection (stereogram) of Fig. 1 imagine you are looking down on the upper half of a sphere projected to a diametral plane (the plane of the paper) by drawing straight lines (projectors) from each point you wish located on this hemisphere to the nadir. Where these projectors cut the projection plane is the point (called a "face-pole") representing in the projection the given point on the hemispherical surface. Consider the projection plane as tangent to the earth at the top of the vertical drillhole, and oriented as shown by the compass-markings. The length of any radius of the divided circle thus represents a 90° vertical arc on this hemisphere; O is the projection of the zenith, z; the divided circle is the basal rim of the hemisphere both in space and as projected (*i.e.*, these two coincide in space). Plot face-pole H along a radius pointing S. 5° W. and out from O a distance such that $OH = R \tan \frac{30°}{2}$, where R = the radius of the divided circle (commonly taken

as 5 centimeters, but reduced from this in the accompanying figures) and the angle plotted = $\tan\left(\frac{90 - H}{2}\right)$. Under these conditions $OH = 5 \times .268 = 1.33$ cms. Plotting of such a face-pole and all later work is greatly facilitated by the use of the new projection protractor.[3] No trigonometric tables are needed; one plots from a scale as easily as any other units (*e.g.*, centimeters) are laid off. If the projection is properly visualized it will be seen that *HO* of Fig. 1 represents the 30° arc *hz* on the sphere (small letters represent points on the sphere corresponding to face-poles of Fig. 1). Or the radius *hO* of the sphere represents the drillhole dipping 60° towards N. 5° E. The line *zO* of the sphere (projected as point *O*) represents the vertical drillhole, and circle *V* of radius = $R \tan\left(\frac{90 - V}{2}\right) = 1.82$ cms. and center *O* represents the locus of all face-poles of all possible beds dipping at a 40° angle. Beds and other planes are plotted as face-poles from points where a diameter of the sphere normal to the bed cuts the upper hemisphere. Now with stereographic center *H* and radius of $(90 - I)°$ draw the small circle *I*. This is done by placing the top scale of the projection protractor [4] along the diameter through *OH* with its zero-point at *O* and counting off 70° either way from *H*. This locates *V'* and *I'*. Bisect *V'I'* with a centimeter scale locating *C*, the geometric center of the required circle *I*, now drawn with an ordinary compass. The two circles *V* and *I* intersect in but one point, *V'*; hence this particular problem has a unique solution represented by *OV'*; whence *D* = 40° to N. 5° E. (given erroneously as 45° in the original). Note that $OV' = \tan\frac{40°}{2}$, since $OV' = 1.82$ cms.

[4] In the absence of the projection protractor, *V'* and *I'* can be located as follows. $HI' = \left[R \tan\left(\frac{70 + 30}{2}\right)\right] - OH = 4.63$ cms. and $HV' = OH + \left[R \tan\left(\frac{70 - 30}{2}\right)\right] = 3.15$ cms. Note $90 - I = 70°$ and $OH = 90 - H = 30°$. The general formulæ here are thus $HI' = \left[R \tan\left(\frac{180 - (I + H)}{2}\right)\right] - OH$ and

$$HV' = OH + \left[R \tan\left(\frac{H - I}{2}\right)\right].$$

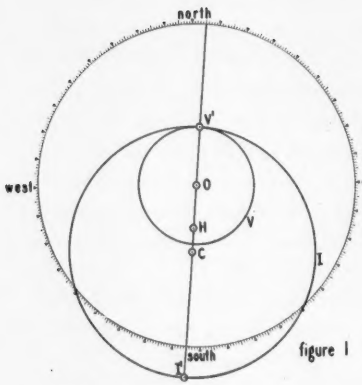

figure 1

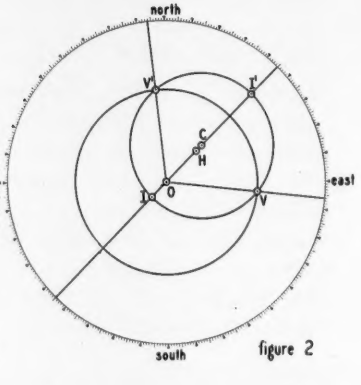

figure 2

Visualize bedding-normals in the vertical hole for all possible cases of dip as represented by the generatrix of a circular cone with apex at the center of the sphere O and cutting the sphere in the v circle. Similarly for the inclined hole the bedding-normals are represented by the generatrix of a circular cone with apex at the center of the sphere O and cutting the sphere in the i circle. The two cones intersect along the line Ov' of the sphere, and so this represents the only bedding-normal in common, and therefore the only possible true one.

PROBLEM II.

$H = 60°$ to S. 45° W.; $V = 30°$; $I = 45°$; $D =$ ———?

In the stereogram of Fig. 2 draw the circle VV' with center O and radius $= R \tan\left(\frac{90 - V}{2}\right) = 2.89$ cms. Locate H on a radius bearing N. 45° E. such that $OH = R \tan\left(\frac{90 - H}{2}\right) = 1.34$ cms. Lay the top scale of the projection protractor [5] on the diameter through OH with its zero-point at O and count off $(90 - I) = 45°$

[5] With no projection protractor make $HI = OH + \left[R \tan\left(\frac{45 - 30}{2}\right)\right] = 0.66$ cms. and $HI' = \left[R \tan\left(\frac{45 + 30}{2}\right)\right] - OH = 2.50$ cms.

either way from H locating I and I'. Bisect II' giving C, the geometric center of the required circle intersecting the first circle at V and V'. This problem thus has two possible solutions represented by OV and OV'. The former gives $D = 60°$ to S. 84° E. and the latter has $D = 60°$ to N. 6° W.

PROBLEM III.

$H = 50°$ to S. 20° W.; $V = 30°$; $I = 10°$; $D =$ ———?

In Fig. 3 draw the V circle centered at O with radius $= R \tan\left(\frac{90 - V}{2}\right) = 2.89$ cms. Locate H on the N. 20° E. radius such that $OH = R \tan\left(\frac{90 - H}{2}\right) = 1.82$ cms. With the top scale of the projection protractor along OH with its zero-point at O locate I and I' out $(90 - I) = 80°$ from H.[6] Bisect II' locating center C of the I circle, and draw it. The I circle at first sight seems to intersect the V circle only at points V and V', but note that point I' is on the lower hemisphere 30° $(= PI')$ below the divided circle. Now $V''P$ is exactly 30°; thus it is clear that if I' were drawn on the projection plane as if projected from its position on the lower hemisphere towards the zenith z of the sphere, it would form part of dashed-line arc $EV''G$ with center at C', located by perpendicular bisectors to straight-lines EV'' and $V''G$.[7] Thus circle I really intersects the V circle at 3 points, V, V', and V'' giving 3 possible solutions, as follows:

For $OV \rightarrow D = 60°$ to S. 48° E.
For $OV' \rightarrow D = 60°$ to S. 88° W.
For $OV'' \rightarrow D = 60°$ to S. 20° W.[8]

[6] In the absence of a projection protractor make $HI = OH + \left[R \tan\left(\frac{80 - 40}{2}\right)\right] = 3.64$ cms. and $HI' = \left[R \tan\left(\frac{80 + 40}{2}\right)\right] - OH = 6.84$ cms.

[7] This center may be found using the methods given earlier by imagining that one is drawing the same circle but with center at H' (on the *lower* hemisphere) antipodal to H. In this case the circle has a radius of $180° - (90 - I) = 100° = H'V''$.

[8] Direction of dip is 180° from that shown in the figure, since the dashed-line circle is projected to the zenith. It could have been drawn as a continuous-line circle (projected to the nadir) tangent to the V circle diametrically opposite V'', then going through E' and G', points on the divided circle diametrically opposite E and G.

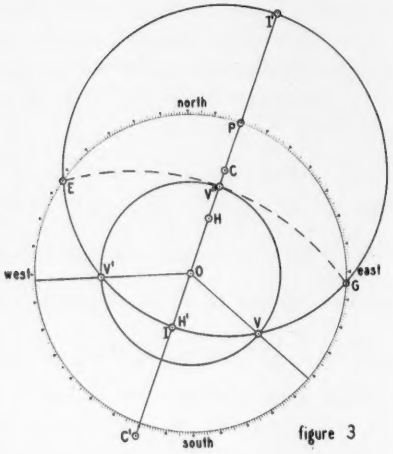

figure 3

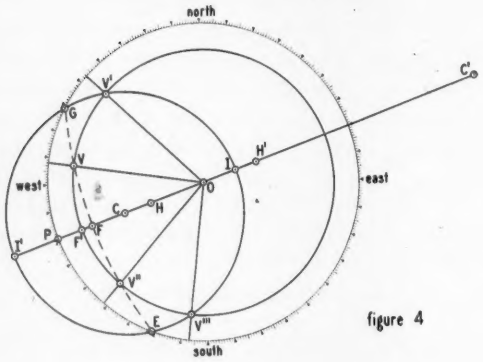

figure 4

PROBLEM IV.

$H = 50°$ to N. 70° E.; $V = 10°$; $I = 25°$; $D =$ ———?

In the stereogram of Fig. 4 draw the V circle with center at O and radius $= R \tan\left(\frac{90 - V}{2}\right) = 4.20$ cms. Plot H on the radius bearing S. 70° W. so that $OH = R \tan\left(\frac{90 - H}{2}\right) = 1.82$ cms. With

the top scale of the projection protractor along OH with its zero-point at O locate I and I' out $(90 - I) = 65°$ from H.[9] Bisect II' locating center C of the I circle, which cuts the first circle at V' and V''. But here again the I circle extends $PI' = 15°$ over on to the lower hemisphere, and yet the V circle along the same diameter (OH) reaches within $PF' = 10°$ of the base of the upper hemisphere. Lay off $PF = 15°$ (note $OF = R \tan \frac{75}{2} = 3.84$ cms.) and draw the dashed-line circle (projected from the lower hemisphere to the zenith z) EFG with center at C'; the latter is found by perpendicular bisectors to straight lines EF and FG.[10] Thus circle I really intersects the V circle at 4 points, V, V', V''', and V'', giving 4 possible solutions, as follows:

For $OV \quad \rightarrow D = 80°$ to S. 82° E.[8]
For $OV' \quad \rightarrow D = 80°$ to N. 47° W.
For $OV''' \rightarrow D = 80°$ to N. 41½° E.[8]
For $OV'' \rightarrow D = 80°$ to S. 7° W.

PROBLEM V.

It may be well to add problems like II and IV but involving two non-vertical drill holes H and K with core-bedding angles of I and J respectively. A problem with but two solutions is taken for V.
$H = 40°$ to S. 60° W. and $I = 50°$; $\quad K = 70°$ to S. 70° E. and

$$J = 30°; \qquad D = \text{———}?$$

Plot H on the radius bearing N. 60° E. so that

$$OH = R \tan \left(\frac{90 - H}{2} \right) = 2.33 \text{ cms.}$$

Plot K on the radius bearing N. 70° W. so that

$$OK = R \tan \left(\frac{90 - K}{2} \right) = 0.88 \text{ cms.}$$

[9] With no projection protractor make $HI = OH + \left[R \tan \left(\frac{65 - 40}{2} \right) \right] = 2.93$ cms. and $HI' = \left[R \tan \left(\frac{65 + 40}{2} \right) \right] - OH = 4.70$ cms.

[10] This center may be found using the methods given earlier by imagining that one is drawing the same circle but with center H' (on the *lower* hemisphere) antipodal to H. In this case the circle has a radius of $180° - (90 - I) = 115° = H'F$.

With the upper scale of the projection protractor along OH with its zero-point at O locate I and $I' = 90 - I = 40°$ from H. Similarly locate along OK points J and $J' = 90 - J = 60°$ from K.[11] Bisect II' locating center C and describe the I circle; bisect JJ' locating C' and draw the J circle. The two circles intersect at 2 points D and

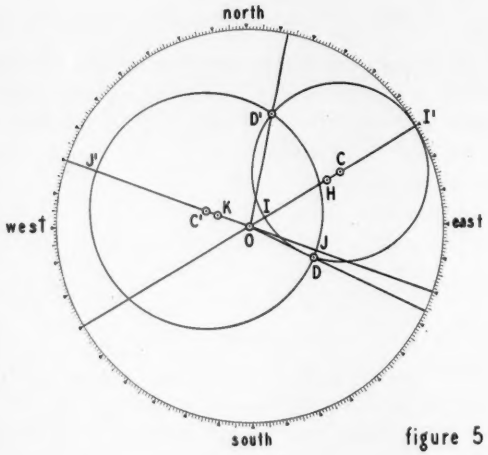

figure 5

D' giving solutions: dip (for OD) = 40° to S. 64° E. and dip (for OD') = 61° to N. 12° E. The strikes are at right angles to these dip directions.

PROBLEM VI.

This resembles the previous example, except that there are four possible solutions.

$H = 50°$ to S. 60° W. and $I = 20°$; $K = 40°$ to N. 40° E. and $J = 50°$; $D =$ ———?

[11] In the absence of a projection protractor make $HI = OH - \left[R \tan\left(\frac{50 - 40}{2}\right)\right]$ = 1.89 cms. and $HI' = \left[R \tan\left(\frac{50 + 40}{2}\right)\right] - OH$ = 2.67 cms. Similarly $KJ = OK + \left[R \tan\left(\frac{60 - 20}{2}\right)\right]$ = 2.70 cms. and $KJ' = \left[R \tan\left(\frac{60 + 20}{2}\right)\right] - OK$ = 3.32 cms.

In Fig. 6 plot H on the N. 60° E. radius out $(90 - H)° = 40°$ from O. Locate I and $\bar{I}'$ on the diameter through H and $(90 - I)° = 70°$ from H. Bisect $I\bar{I}'$ giving C and with this as center describe the circle EIG. Establish points antipodal [12] to all these and draw circle $E'\bar{I}G'$. Note that points in the projection designated by letters with a bar above them (as $\bar{I}$, read "bar-eye") represent points which lie on the lower hemisphere; lines so located are dashed. These two circles thus represent the stereographic projection of a

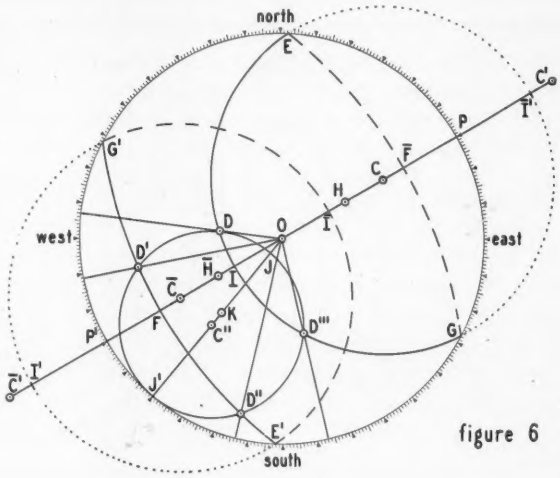

figure 6

double cone with a single axis $H\bar{H}$, a half-apical angle of 70°, and a common apex point at O, the center of the sphere. Locate $\bar{F}$ on the diameter through H so that $P\bar{F} = P\bar{I}'$ $(= 20°)$ and make F antipodal to $\bar{F}$. Draw arcs $E\bar{F}G$ and $E'FG'$ with centers at $\bar{C}'$ and C' respectively. Then dotted-line arc $E\bar{I}'G$ (projected to the nadir) = dashed-line arc $E\bar{F}G$ (projected to the zenith), and this arc actually lies on the lower hemisphere. Similarly dotted-line arc $E'I'G'$ (projected to the zenith) = arc $E'FG'$ (projected to the

[12] Antipodal points are those at opposite ends of any diameter of the sphere, such as E and E', H and $\bar{H}$. Such points lie on the same diameter in the projection and equidistant from its center O.

nadir), and this arc actually lies on the upper hemisphere and is antipodal to dashed-line arc $E\bar{F}G$. All this explanation is to help the reader form a visual picture of the problem; to solve it, only the two arcs shown by continuous lines need be drawn.

Plot K on the S. 40 W. radius out $(90 - K)° = 50°$ from O and establish J and J' on the radius through K out $(90 - J)° = 40°$ from K. Bisect JJ' locating C'' and with this as center strike a circle of 40° radius intersecting the two continuous-line arcs previously drawn at D, D', D'', and D'''. The vectors from O to these points give the required four possible solutions, as follows:

For OD $\rightarrow D = 34\frac{1}{2}°$ to N. 83° W.
For OD' $\rightarrow D = 72°$ to S. 79° W.
For OD'' $\rightarrow D = 82\frac{1}{2}°$ to S. $13\frac{1}{2}°$ W.
For OD''' $\rightarrow D = 50\frac{1}{2}°$ to S. 13° E.

Of course problems involving three holes may be solved by the same principles as those given earlier. The graphical picture afforded by the projection provides the opportunity for much discretion in the selection of the bearing and dip of a second hole. This matter is discussed by both Mead [13] and Wisser.[14] Moreover in case there is no solution, the stereographic method is fine, since the V and I circles might not intersect. This would imply errors in data or graphing, or else that the bed (fault, vein) whose attitude was wanted was not planar or was displaced by faulting between the holes.

UNIVERSITY OF CHICAGO,
CHICAGO, ILLINOIS,
February 26, 1941.

[13] Mead, Warren J.: Determination of attitude of concealed bedded formations by diamond drilling. Econ. Geol., 16: 37–47, 1921.

[14] Wisser, Edward: An aid in the interpretation of diamond drill cores. Econ. Geol., 27: 437–449, 1932.

DISCUSSION AND COMMUNICATIONS

AN IMPROVED TECHNIC FOR THE MAKING OF THINNED POLISHED SECTIONS.

Sir: Information regarding the making of combination sections of rocks and ores has been published in the earlier volumes of this journal. The investigation both in transmitted and reflected light can with advantage be carried out by the aid of these slides. Two types of combined polished and thin sections have been introduced, viz., the thinned polished sections described by Donnay[1] and the polished thin sections, the making and properties of which, in comparison with the first-mentioned sections, have been discussed by Grondijs and Schouten.[2]

The general drawbacks of the polished thin sections include difficulties during their preparation, a more or less unsatisfactory polish, and quick tarnishing in the air. The number of repolishings is limited by the thinness of the slide, and only one, if any, etching is possible.[3] The versatility of the thinned polished sections, on the other hand, is greatly affected by the limited amount of possible magnifications due to the use of a cover-glass, the lack of etching possibilities in the finished slides, the overstrain in the superficial layer, and by the delicate operation of a transfer of a mere film of rock on to a cover-glass.[4]

Since the combination sections are not used in order to discard real polished sections, but merely as an aid to textural and para-

[1] Donnay, J. D. H.: Thinned polished sections. A new technique for the investigation of ores in thin slices. ECON. GEOL., 25: 270–274, 1930.

[2] Grondijs, H. F. and Schouten, C.: Polished thin sections of ore and rock. ECON. GEOL., 26: 343–345, 1931.

[3] Schneiderhöhn, H. und Ramdohr, P.: Lehrbuch der Erzmikroskopie. I: 1, p. 89, Berlin 1934.

[4] Grondijs, H. F. and Schouten, C.: Op. cit., p. 344.

genetic investigations, the fact that the thinned polished sections are covered by glass plays no important rôle. These sections, with their good keeping properties, are in the author's opinion superior to the polished thin sections. The weak point in their preparation being the transfer of the thin rock section to the cover-glass, the following technic was adopted to facilitate the making of these sections and has been successfully used for a number of rocks and ores.

A chip of the rock is polished in the usual manner and the result obtained checked by the aid of the reflecting microscope in order to ensure a good and even polish. The chip is mounted on a cover-glass with its polished surface against the glass, the cover-glass in its turn being mounted on a mounting-glass. The chip is ground down until a thickness of .03 mm. is obtained. Next, the mounting-glass is removed. For this purpose the mounting medium around the borders of the cover-glass is scratched away, and the cover-glass with the slide loosened with a thin blade. The Canada balsam used as a mounting medium being brittle, no difficulties will be encountered in this procedure. Finally, a mounting-glass is coated with a layer of fluid Canada balsam which is heated until a suitable thickness is obtained, and the thinned polished section is mounted on the glass. It is advisable to avoid overheating of the Canada balsam since the slides otherwise may contain air bubbles and partly break up.

Under the cover-glass the section is well protected from tarnishing. As a matter of fact, a section with chalcopyrite stored for three years showed no changes of color in that mineral whatever.

Due to internal reflections in the glass cover, the contacts between the minerals are blurred and a satisfactory focussing is prevented. To overcome this, Donnay[5] recommends the use of oil immersion lenses. However, in the author's practice this trouble is greatly diminished by the use of modern objectives, *e.g.*, the "Epilum" objectives of Reichert, which allow of satisfactory

[5] Donnay J. D. H.: Op. cit., p. 272.

pictures being obtained with magnifications up to appr. 540 diam., where a limit is set by the thickness of the cover-glass.

In addition to the uses of the combination sections presented by Donnay[6] and by Grondijs and Schouten,[7] their use when studying diamond drill cores is suggested. Here the available material is usually sparse, and for a general survey at least, observations in addition to those which can be obtained from ordinary thin slices might prove to be of some value, the more so, as the preparation of the slides can be carried out in but little more time than that needed for the making of ordinary thin sections.

The author's thanks are due to Mr. H. Nyberg for the preparation of the thinned polished sections.

KALERVO RANKAMA.

MINERALOGICAL AND GEOLOGICAL INSTITUTE,
UNIVERSITY OF HELSINKI, FINLAND,
March 5, 1941.

[6] Donnay, J. D. H.: Op. cit., pp. 270, 274.

[7] Grondijs, H. F. and Schouten, C.: Op. cit., p. 345.

REVIEWS *

Dana's Manual of Mineralogy, 15th Edit. Revised by C. S. HURLBUT, JR. Pp. 470. John Wiley and Sons, New York, 1941. Price, $4.00.

The "Manual," intended for the student of elementary mineralogy, is a junior companion of the well known "Textbook of Mineralogy," and this edition will give it an existence of nearly a century. The page size is now 6 by 9 inches. The book has in large part been rewritten but the scope is little changed although numerous additions are noticeable. It is still designed for the student, the mining engineer, the geologist, and the amateur. A section on "Mineral Uses" has been added and the classification of minerals has been changed to conform with that in the forthcoming *System of Mineralogy*. The mineral index is now more convenient because it carries the composition, system, gravity, hardness, and remarks. One hundred and ninety-seven minerals are described and one hundred and twenty are mentioned casually. This revision should continue to make the "Manual" the most widely used elementary text on mineralogy.

The Time of Origin and Accumulation of Petroleum. By F. M. VAN TUYL AND BEN H. PARKER. Pages 180; Figs. 4. Colorado School of Mines Quarterly, Golden, Colorado. Vol. 36, No. 2, April, 1941. Price, $2.00.

By means of a carefully worked out questionnaire the authors, under the sponsorship of the Research Committee of the A. A. P. G., have assembled information from 48 contributors in the United States and abroad, relative to 23 fundamental problems of petroleum geology. The answers to each question are assembled under separate chapter headings. Two final chapters consist of "Miscellaneous Comments" and "Deductions and Conclusions."

Methods of Study of Sediments. By W. H. TWENHOFEL AND S. A. TYLER. Pages 183; Figs. 17; Tables 24. McGraw-Hill Book Co., New York, 1941. $2.00.

This small manual to be used by students and by workers in commercial laboratories contains the most useful sedimentary techniques, assembled

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, W. S. Bayley, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

from scattered sources. The various chapters relate to collection, preparation, mechanical analysis and mineral separation of sediments; quantitative determination of mineral content, graphical representation, chemical methods, physical properties of sediments, coals, and mounting. The authors have attempted to give detailed consideration to the various methods of study on their individual merit. Whether or not they have succeeded will undoubtedly be a matter of personal opinion.

Geological Map of Red Lake Area, Ontario. By H. C. HORWOOD. Sheets 49a (West), 49b (East) both colored. Scale, 1:31,680; size 72 × 44; 15 colors. Also Sheet 49c "Bateman Township-Coli Lake-Trout Lake Area," 19 × 22, uncolored.

These are the largest detailed maps ever published by the Ontario Department of Mines. All formations are shown in two-tone colors, the darker to represent actual outcrops (very valuable) and the lighter to indicate the probable extent of the formations. Sixteen townships are included. These maps are a new advance in Canadian geological mapping and the author and the Department are to be congratulated.

The Last Million Years. By A. P. COLEMAN, edited by G. F. KAY. Pp. 216. Univ. of Toronto Press, Toronto, Canada, 1941. Price $3.50.

This volume deals with Pleistocene glaciation and represents the results of 50 years of observations by the author. The manuscript was interrupted by the author's death and was completed and brought up to date by Professor Kay. Although most of the material is not new, the discussions of the Interglacial events around Toronto contain new contributions, and the whole subject of Pleistocene glaciation is concisely brought together in very readable form. The story is discussed in a simple way for the layman and glaciologist alike.

BOOKS RECEIVED.

WILLIAM E. BENSON.

Geologic Formations and Economic Development of Oil and Gas Fields of Cal., Pt. 1-Development of the Industry. J. R. PEMBERTON, G. S. BORDEN, H. L. SCARBOROUGH, W. R. WARDNER, JR., R. M. BAUER, AND J. F. DODGE. Pp. 80; figs. 34; numerous unnumbered tables. Cal. Div. Mines Bull. 118, Pt. 1. Sacramento, 1940.

Investigations in Ore Dressing and Metallurgy. Pp. 194. Canada Bur. Mines, No. 805. Ottawa, 1940. Price, 50 cents. *A detailed description of laboratory and mill run tests with numerous tables and flow sheets.*

Geology of the Southern Alberta Plains. L. S. RUSSELL AND R. W. LANDES. Pp. 217; pls. 8; figs. 21; 3 geol. maps in color, all have scale 1″ = 4 miles. Can. Geol. Surv. Memoir 221. Ottawa, 1940. Price, 50 cents. *Excellent natural size photographs of fossil specimens.*

Geology of Saint John Region, New Brunswick. F. J. ALCOCK. Pp. 62; pls. 4; 3 geol. maps in color, 2 have scale 1/63,360, 1 has scale 1″ = 4 miles. Can. Geol. Surv. Memoir 216. Ottawa, 1938. Price, 25 cents.

Clarion Clay of Hope and Lincoln Furnace Fields. W. STOUT. Pp. 43; numerous unnumbered tables. Ohio Geol. Surv. Bull. 40, 4th series. Columbus, 1940. *Geology, physical and chemical properties of clays.*

The Upper Cretaceous Deposits. L. W. STEPHENSON AND W. H. MONROE. Pp. 282; pls. 15; figs. 48; 2 geol. maps 9″ × 20″, scale 1″ = 8 miles. Miss. Geol. Surv. Bull. 40. University, 1940. *Well illustrated with photographs, those of fossils are especially good.*

The Naturalists' Directory. Pp. 292. Cassino Press. Salem, Mass., 1940. Price, $3.00. *The 32nd. edition of this directory of the leading naturalists of the country.*

The Theory of Ground-Water Motion. M. K. HUBBERT. Pp. 159. Jour. of Geol., vol. 48, 1940, suppl. to no. 8; pp. 785–944. Price, $1.25. *A fundamental, mathematical, theoretical treatise on ground water motion.*

Provisional Geol. Map of Uganda. In color, 28″ × 29″, scale, 1:1,000,000. *Includes parts of Lake Victoria, Upper Nile, and Rift Valley, showing amazing drainage reversals.*

Quicksilver Deposits at Buckskin Peak National Mining District, Humboldt County, Nevada. R. J. ROBERTS. Pp. 18; pls. 3; figs. 5; geol. map 10″ × 12″, scale 1″ = 500 ft. U. S. Geol. Surv. Bull. 922-E, Prelim. Rept. Washington, 1940. Price, 15 cents.

Tungsten Deposits of Boulder County, Colorado. T. S. LOVERING. Pp. 21; pls. 2; figs. 6; geol map 14″ × 16″, scale 1/62,500. U. S. Geol. Surv. Bull. 922-F. Washington, 1940. Price, 20 cents.

Copper Deposits of Newfoundland. G. V. DOUGLAS, D. WILLIAMS, AND O. N. ROVE. Pp. 171; pls. 32; figs. 22; tables 20. Newfoundland Geol. Surv. Bull. No. 20. St. John's, 1940. *Descriptions of all actual and potential copper producing areas of Newfoundland. Well illustrated with numerous excellent geologic maps, magnetic survey maps, and cross sections of mines. Emphasizes economic considerations.*

Oklahoma Geol. Surv. and Industrial Development, Director's Biennial Report, 1939–40. Pp. 28; pls. 13; tables 3. Norman, Dec. 1940. *Discusses status and needs of mineral industry and the Geol. Surv. of Oklahoma.*

Geology and Oil Possibilities of Extreme Southern Illinois. J. M. WELLER. Pp. 64; figs. 1: structure cont. map 32″ × 40″, scale 1″ = 8

miles. Ill. Geol. Surv., Inves. Rept. No. 71. Urbana, 1940. *Gives detailed stratigraphy and data from well logs.*

Preliminary Geologic Map of Parts of the Alto Pass, Jonesboro, and Thebes Quadrangles. J. M. WELLER AND G. E. EKBLAW. Pp. 21; figs. 2; geol. map 15″ × 35″, scale, 1″ = 1 mile. Ill. Geol. Surv., Inves. Rept. No. 70. Urbana, 1940. *General geology with emphasis on stratigraphy.*

Kansas Geol. Surv., Bulls. 27–32. University of Kansas Press, 1940.

No. 27—Ground Water Resources. R. C. MOORE, S. W. LOHMAN, J. C. FRYE, H. A. WAITE, T. G. MCLAUGHLIN, AND B. LATTA. Pp. 68; pls. 34; figs. 28.

No. 28—Exploration for Oil and Gas in West. Kan. in 1939. W. A. VER WIEBE. Pp. 96; figs. 34.

No. 29—Asphalt Rock in Eastern Kansas. J. M. JEWETT. Pp. 18; pls. 2; figs. 3.

No. 30—Oil and Gas in Linn County. J. M. JEWETT. Pp. 24; pls. 3; figs. 7.

No. 31—Oil and Gas in Montgomery County. G. E. ABERNATHY, R. P. KEROHER AND W. LEE. Pp. 24; pls. 2; figs. 6.

No. 32—Coal Resources of Kansas: Post Cherokee Deposits. R. E. WHITLA. Pp. 57; pls. 5; figs. 28.

No. 33—Subsurface Mississippian Rocks of Kansas. W. LEE. Pp. 106; pls. 10; figs. 4; tables 2. *An excellent collection of papers under one cover.*

The Geology of the Country around Potchefstroom and Klerksdorp. L. T. NEL, F.G.S., F. C. TRUTER, AND J. WILLEMSE. Pp. 122; figs. 2; tables 1. U. S. Africa Geol. Surv., Explanation of Sheet No. 61 (Potchefstroom). Pretoria, 1939.

Economic Aspect of the Boulder Bed on Radhaballavpur near Salanpur, Burdwan District. K. K. SEN GUPTA AND J. SEN GUPTA. Pp. 8; geol. map 8″ × 9″, scale 1½″ = ⅛ mile. Geol., Min. and Met. Soc. of India, Bull. 4. Calcutta, 1940. Price, 2 rupees.

Canada Dept. Mines and Resources, Geol. Surv. Paper 40. *Geologic maps of various parts of Canada sometimes accompanied by short reports. Ottawa, 1940. Price, 10 cents per area. First listed in this journal March–April, 1941. The following new reports have been received.*

No. 40–15 Grave Flats, Alberta. B. R. MACKAY. *Prelim. Map.*

No. 40–16 Pembina Forks, Alberta. B. R. MACKAY. *Prelim. Map plus structure sections.*

No. 40–17 George Creek, Alberta. B. R. MACKAY. *Prelim. Map plus structure sections.*

No. 40–19 Bearberry, Alberta. H. H. BEACH. *Prelim. Map.*

No. 40–20 Assinica Lake, Quebec. G. SHAW. *Prelim. Map.*

No. 40–21 Mishagomish Lake, Quebec. G. SHAW. *Prelim. Map.*

No. 40–22 Natural Gas in Brantford Area, Ontario. J. F. CALEY. Pp. 30; 1 map. *Subsurface geology from well logs and production figures for the area.*

SCIENTIFIC NOTES AND NEWS

D. H. McLAUGHLIN has been appointed Dean of the Colleges of Engineering and Mining of the University of California at Berkeley.

C. W. WRIGHT of the U. S. Bureau of Mines has been recalled from South America to confer on problems of the National Defense Commission.

JOHN PAYNE, JR. is now geologist for the American Metal Co., Ltd. in El Paso.

R. B. MILLER, mineral economist with the U. S. Bureau of Mines, has transferred to a similar position with the Export Control Commission.

Northwestern University has a summer field party studying the pre-Cambrian rocks of the Los Pinos Range, New Mexico, in charge of J. T. STARK and E. C. DAPPLES, assisted by H. GARRISON, J. NORTON, M. STAATZ, and R. WILPOLT. Recent lecturers at Northwestern have included N. M. FENNEMAN on "Desert forms and desert processes"; HARRISON SCHMITT on "The training of the mining geologist"; H. E. MCKINSTRY on "Structural control in certain Australian gold districts"; E. S. BASTIN on "Silver ores as illustrations of problems of the mining geologist"; THERON WASSON on "Petroleum prospecting methods in Latin America"; SHERWIN F. KELLY on "Magnetic and electrical technique in the mining and petroleum fields"; and H. K. GLOYD on "Desert ecology."

P. H. REAGAN of LaPaz has been appointed consulting mining engineer to the U. S. Geological Survey in its study of the tin, tungsten and antimony resources of Bolivia.

W. A. NELSON, professor of economic geology at the University of Virginia, has been appointed staff expert to the Ferrous Alloys and Minerals Branch of the Priorities Division of the Office of Production Management. E. J. HERGENROETHER, metallurgist of International Nickel, J. S. EARLE of American Smelting and Refining Co., and FRANK AYER, formerly general manager of Roan Antelope and Mufulira Copper mines, have also recently been added to the staff of O. P. M. Their duties will be concerned with the conservation of strategic materials, substitutes for such materials and reclamation of scrap metals.

F. D. REID, Canadian mining engineer, received an honorary LL.D. degree in May from his Alma Mater, Queen's University.

G. W. RUST is supervising engineer of the mining section of the Reconstruction Finance Corp. at San Francisco.

W. J. MORLEY has been appointed state mining engineer and chief inspector of mines for Queensland, Australia.

J. J. BEESON, W. R. LANDWEHR, E. J. SCHRADER, and L. S. BRECKON are investigating the geology of the Rip Van Winkle mine in Nevada.

G. C. BATEMAN, Metals Controller, and HERBERT SYMINGTON, Power Controller for Canada, have been appointed to represent the Dominion on a committee to correlate the war-material resources of the United States and Canada.